

# PASCOS 2010

Valencia  
(Spain),  
July 19th-23rd,  
2010

16th  
International  
Symposium on  
**Particles  
Strings and  
Cosmology**

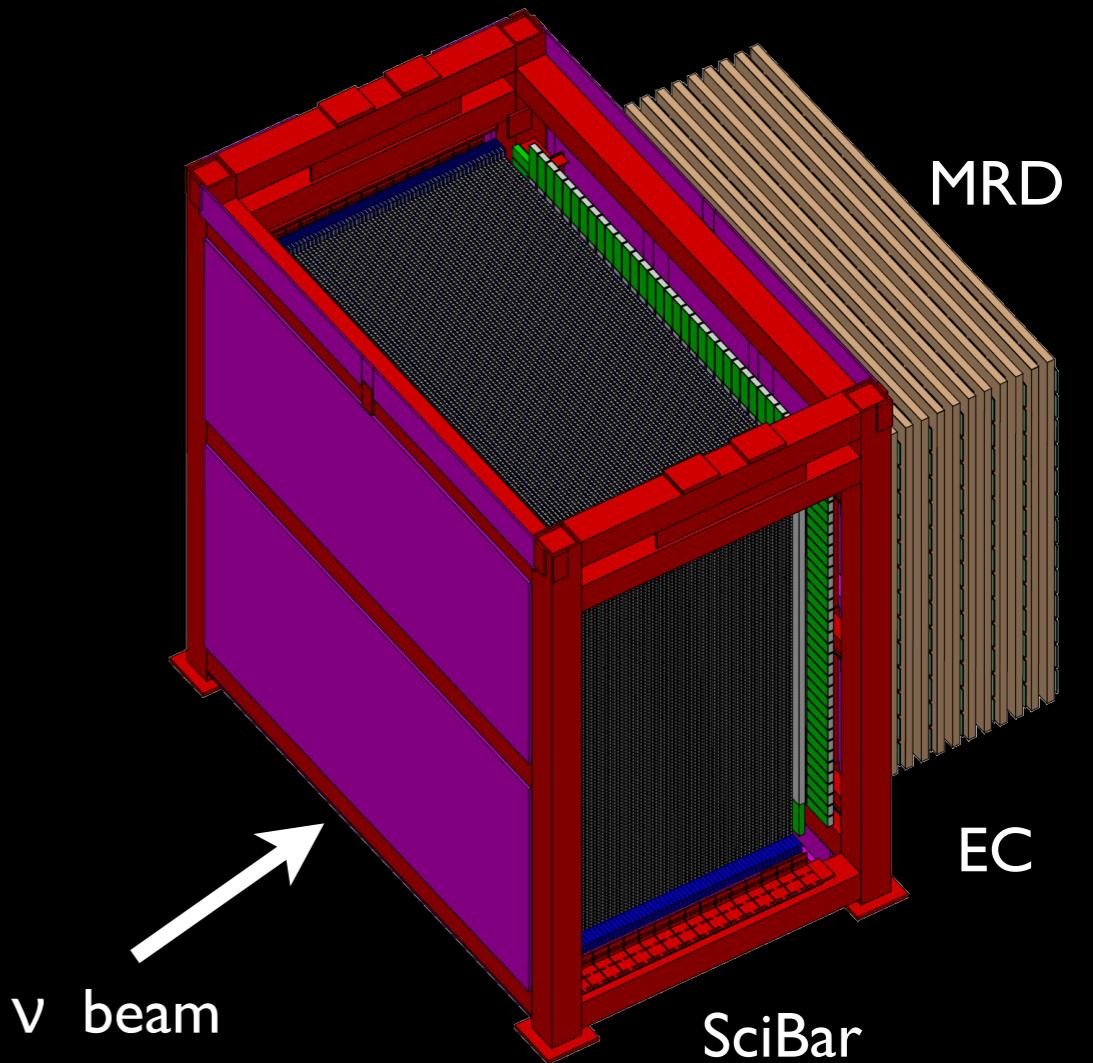
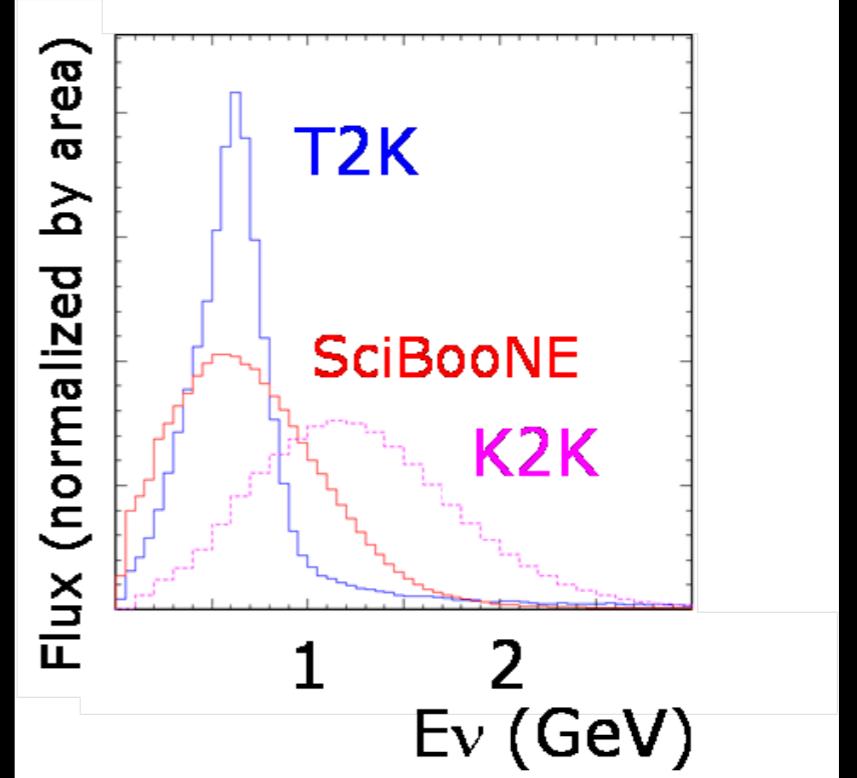
**Low-Energy  
Neutrino Cross  
Sections With  
SciBooNE**

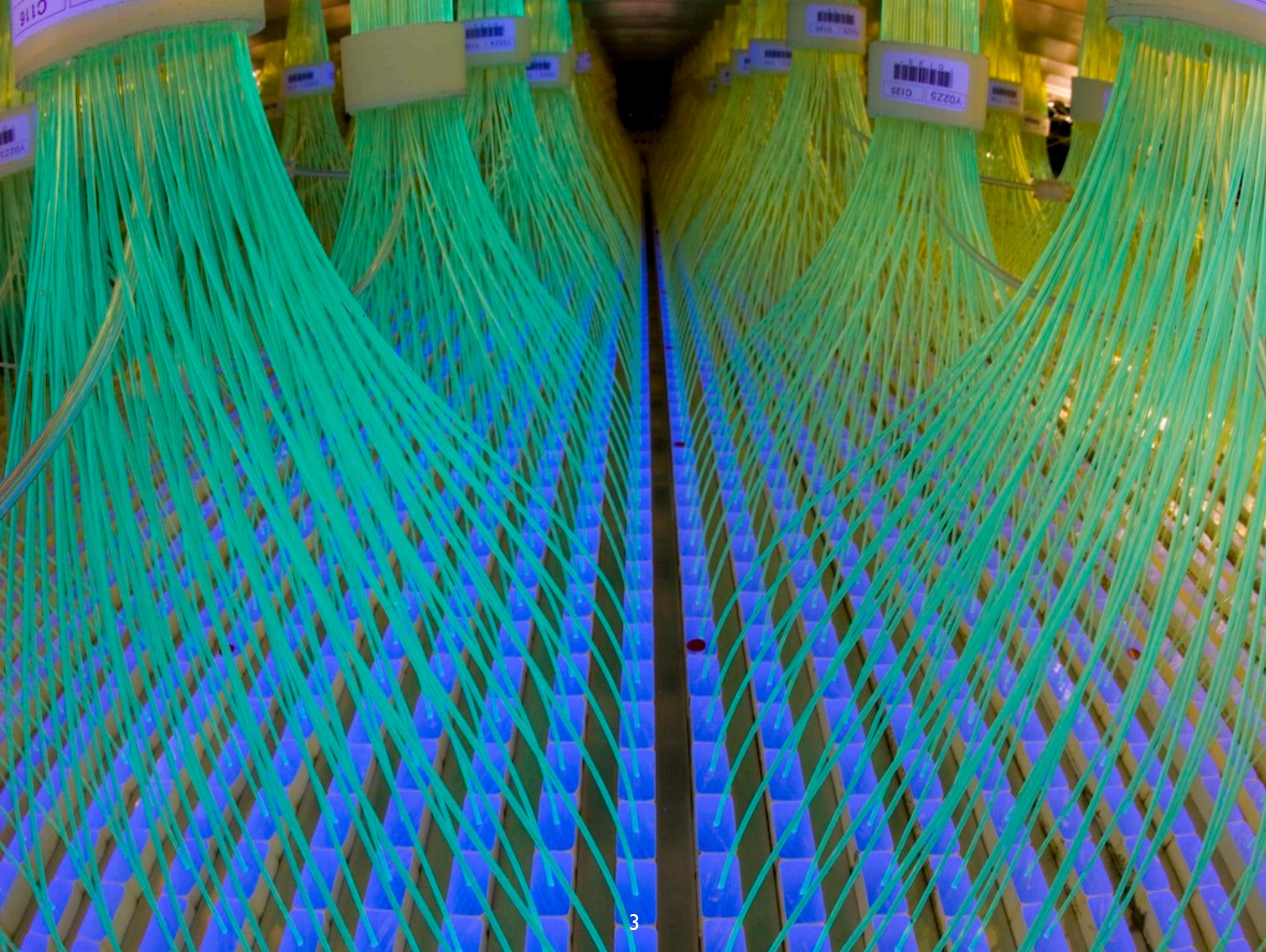
**M. Sorel**

**IFIC  
(CSIC & U. Valencia)**

# SciBooNE

- Neutrino scattering experiment at Fermilab
- Data-taking: 2007-2008
- Precision muon neutrino and muon antineutrino cross-section measurements at  $\sim 1$  GeV
- Near detector in Booster Neutrino Beamline serving also MiniBooNE, soon MicroBooNE  
 $\Rightarrow$  *short-baseline oscillation searches*
- Detector:
  - SciBar: neutrino target + tracker
  - EC: electromagnetic calorimeter
  - MRD: muon range detector





# SciBooNE Collaboration

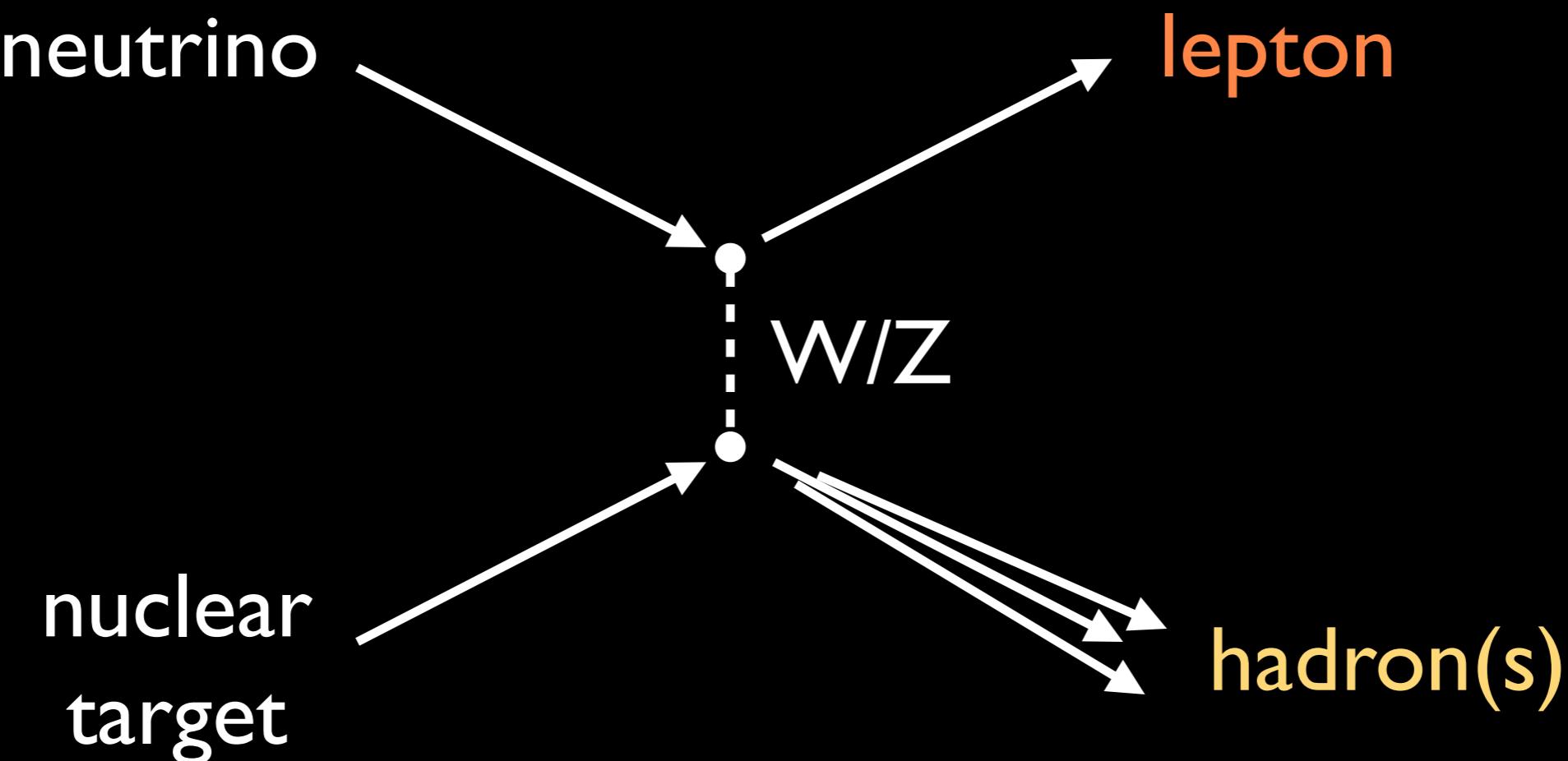


- IFAE (U. Barcelona)
- Brookhaven National Laboratory (BNL)
- University of Colorado, Boulder
- Columbia University
- Fermi National Accelerator Laboratory
- High Energy Accelerator Research Organization (KEK)
- Imperial College London
- Indiana University
- Institute for Cosmic Ray Research (ICRR)
- Kyoto University
- Los Alamos National Laboratory
- Louisiana State University
- Massachusetts Institute of Technology
- Purdue University Calumet
- Universita di Roma "La Sapienza"
- Saint Mary's University of Minnesota
- Tokyo Institute of Technology
- IFIC (CSIC & U. Valencia)

• 5 countries, 18 institutions, ~60 physicists

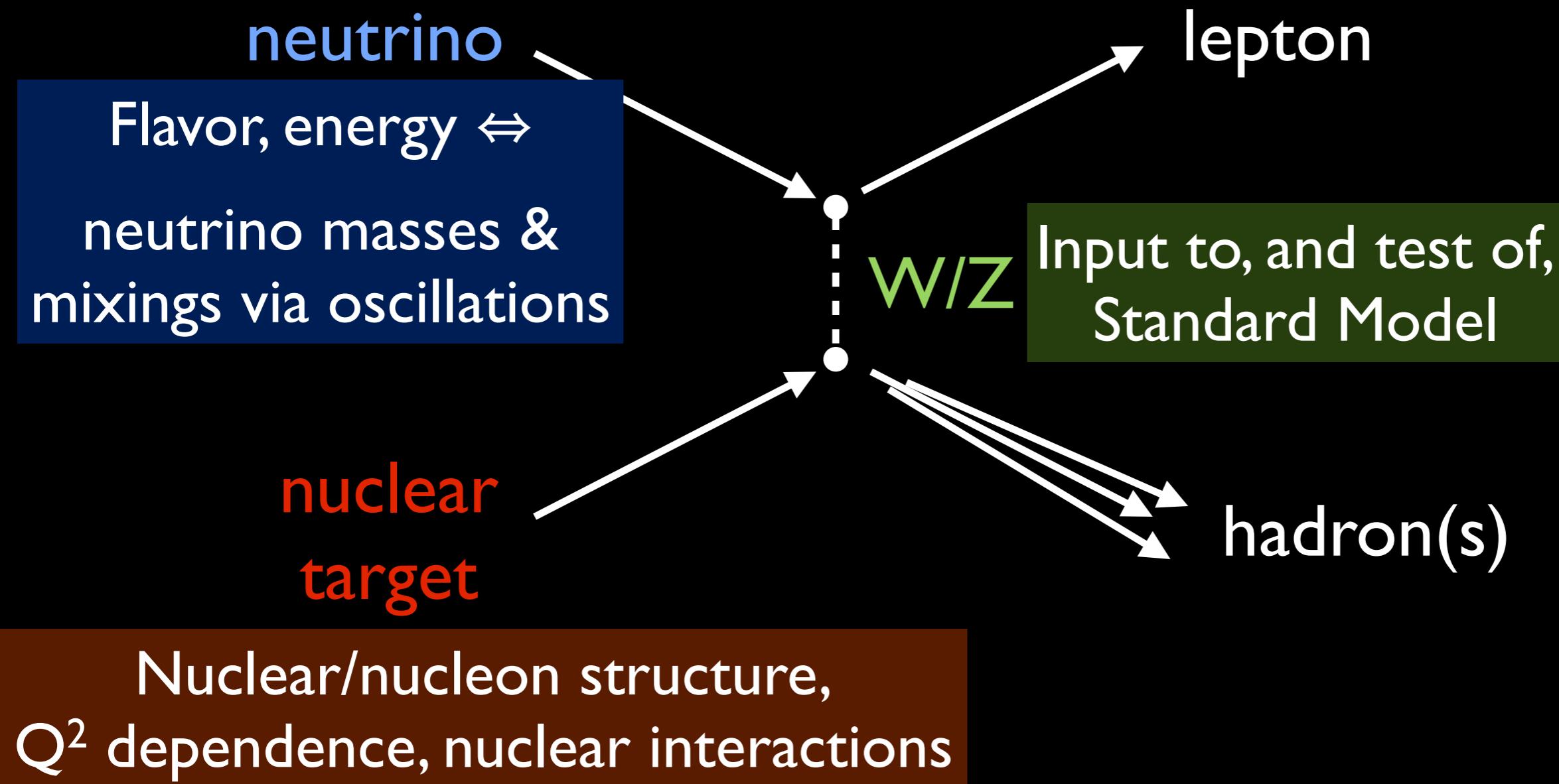
# Why Study Neutrino Interactions?

- Measure final state lepton and/or hadron(s)

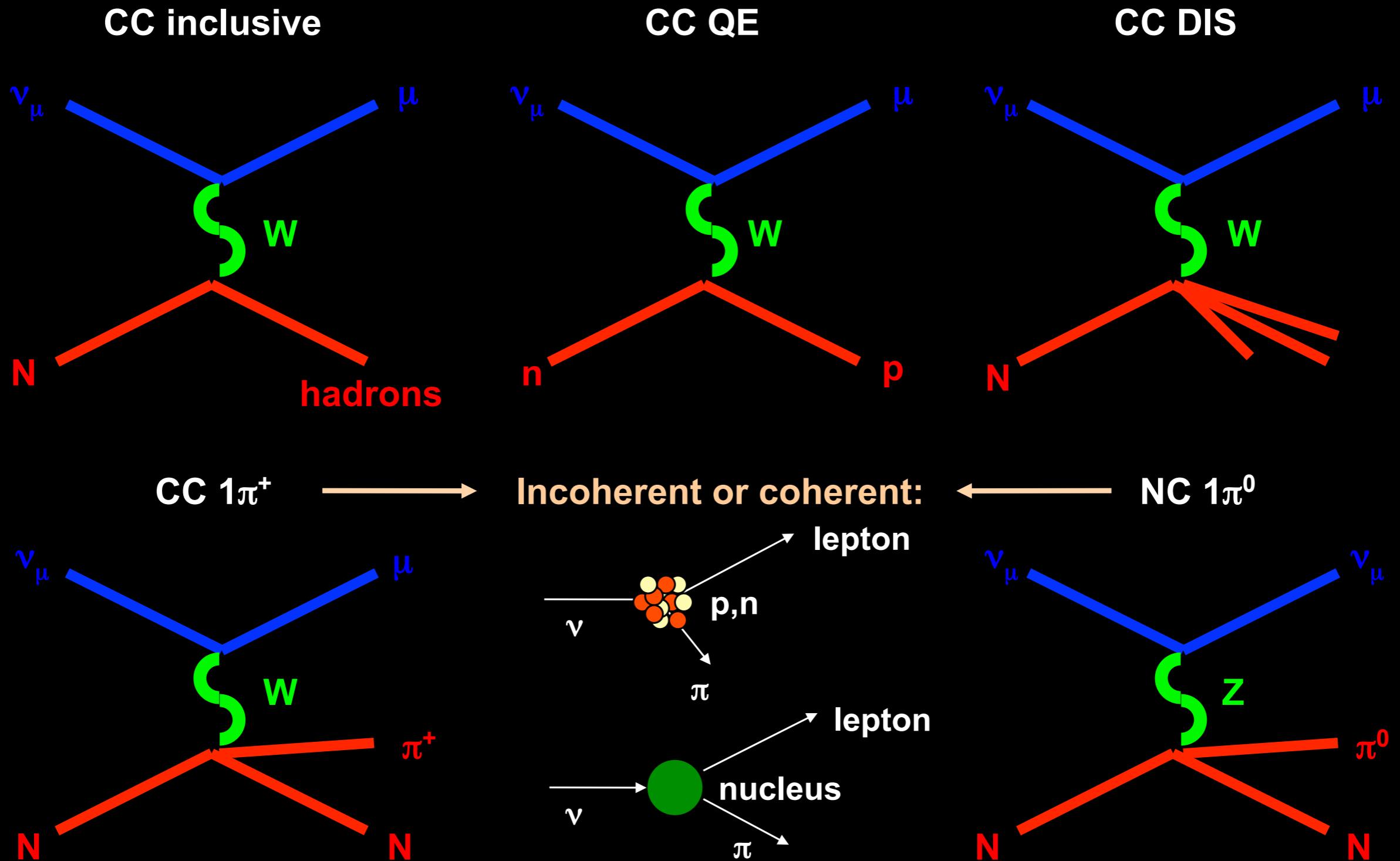


# Why Study Neutrino Interactions?

- Infer **electroweak**, **nuclear**, **neutrino** properties

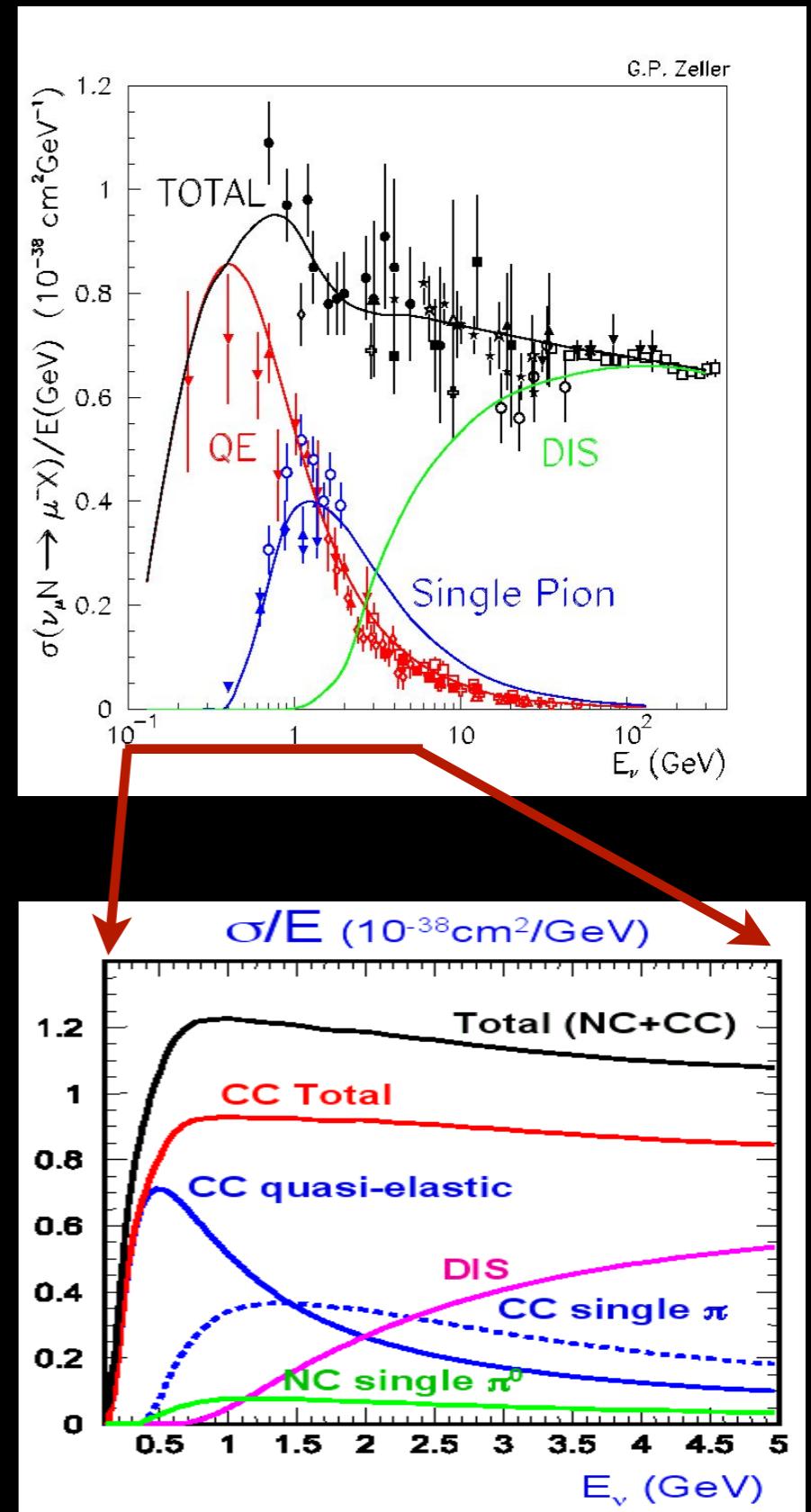


# Some Important Neutrino Interactions

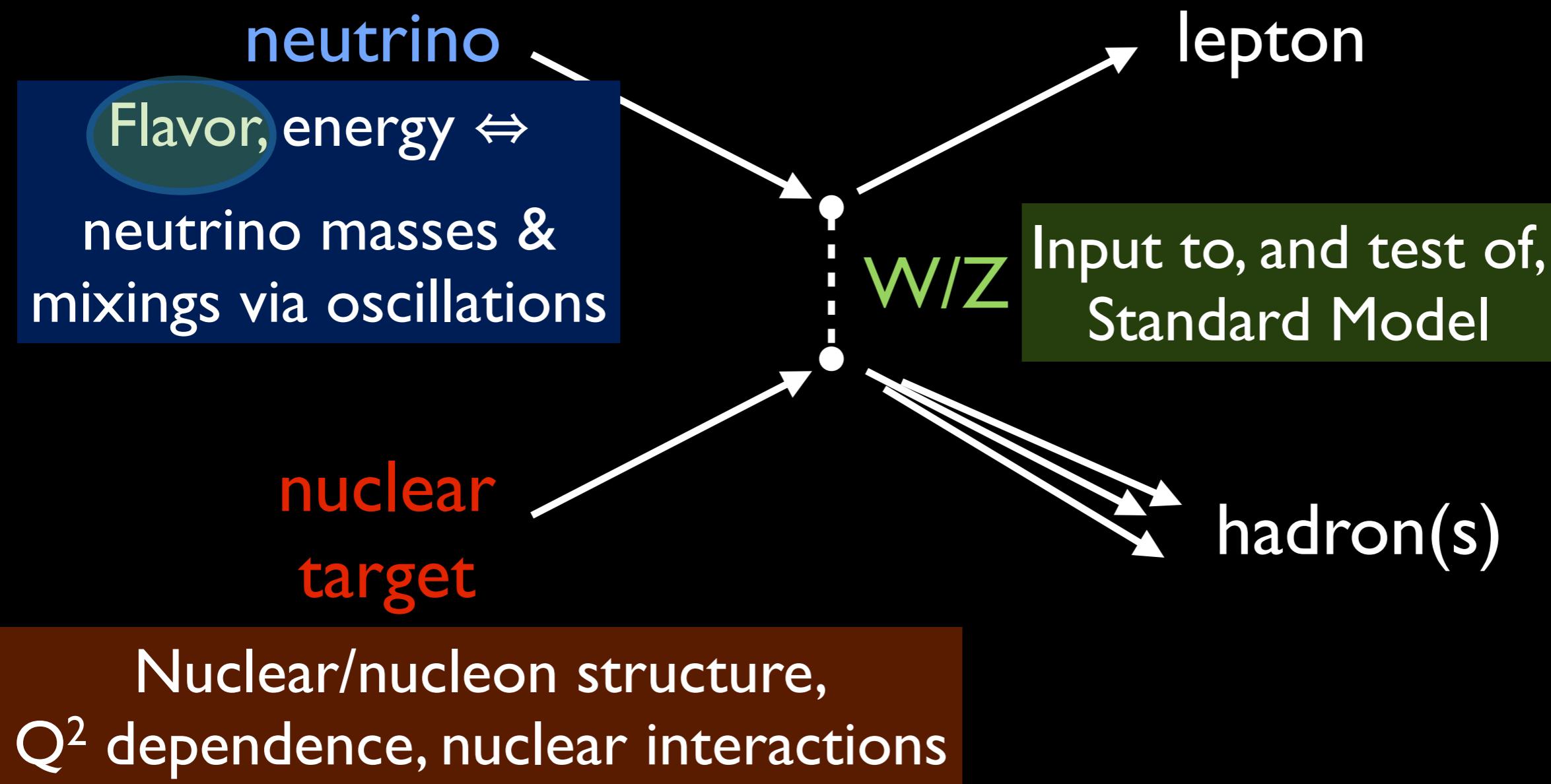


# Current Knowledge

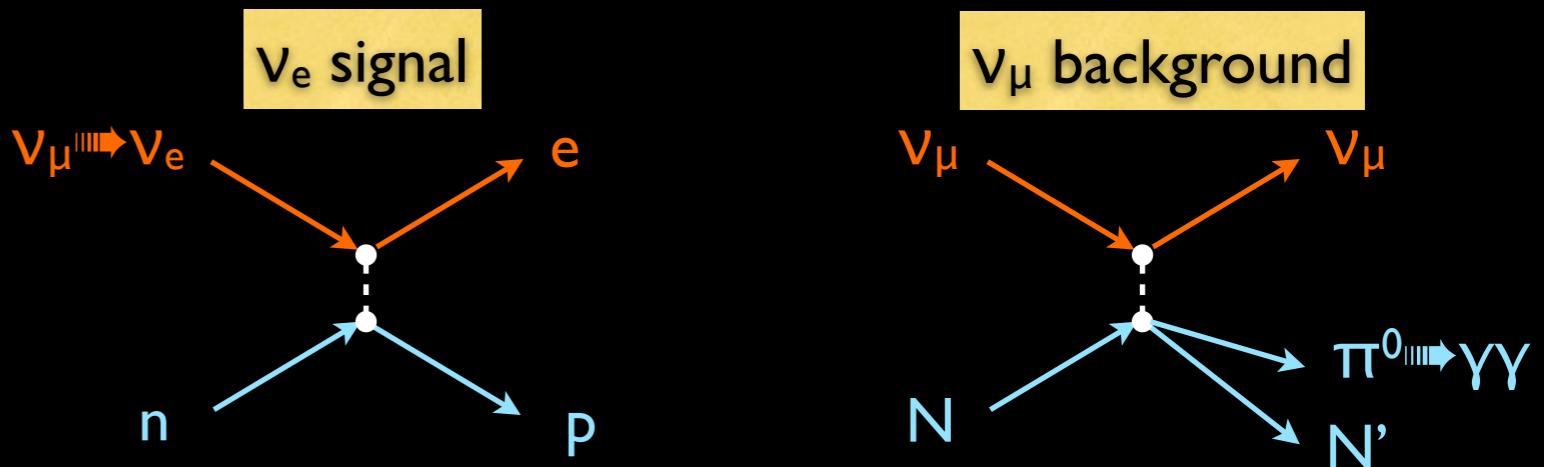
- Relatively precise measurements at high neutrino energies, where deep inelastic scattering dominates
- Less precise measurements in few-GeV region, where many processes contribute
- Scarce data on differential cross-sections
- Effects from nuclear targets important at all energies, especially low energies
- Large uncertainties, many puzzles



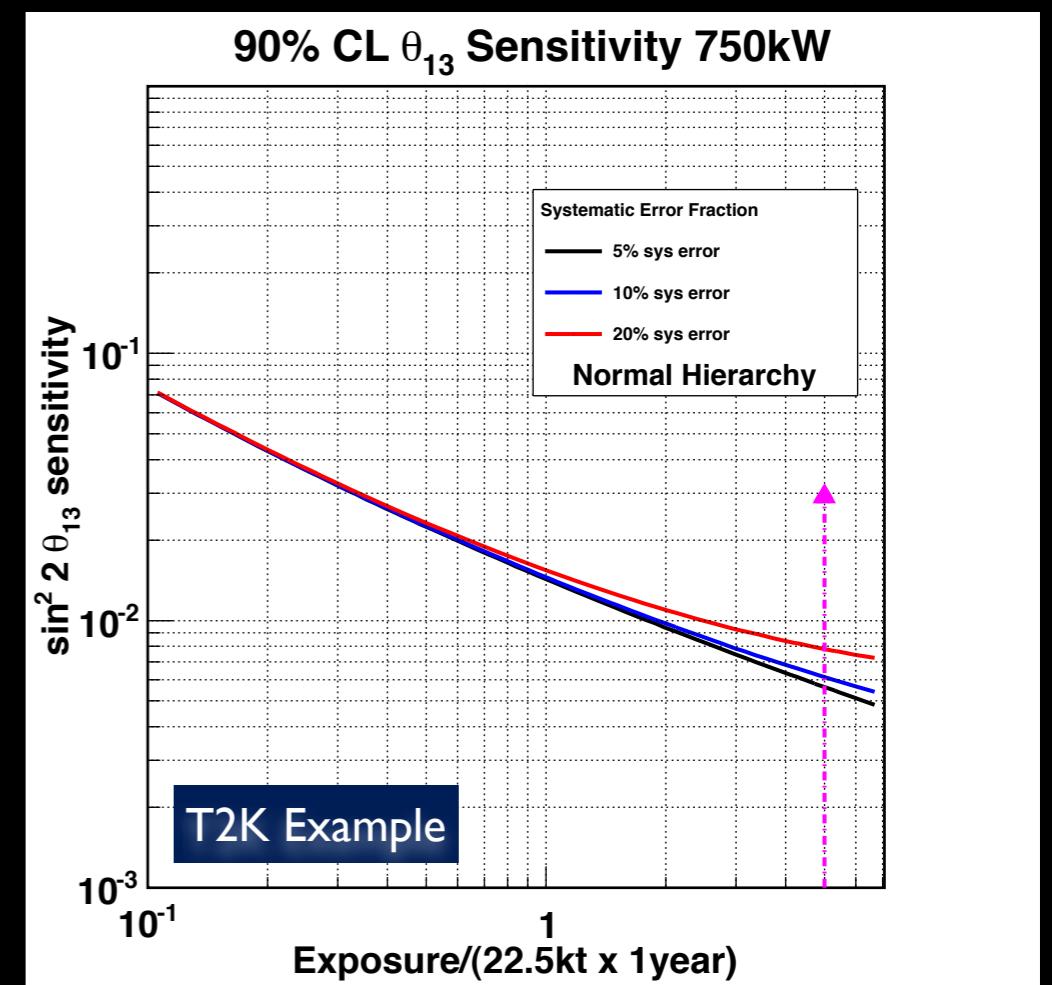
# Neutrino Interactions and Inferring Flavor



# V<sub>e</sub> or V<sub>μ</sub>?



- Main  $\nu_\mu$  background to  $\nu_\mu \rightarrow \nu_e$  searches: **NC single  $\pi^0$  production**
- Two processes cannot be distinguished if one  $\gamma$  is missed in NC- $\text{I}\pi^0$
- Affects oscillation analysis robustness and  $\theta_{13}$  reach if NC- $\text{I}\pi^0$  not understood
- Need to measure:
  - NC- $\text{I}\pi^0$  total cross-section
  - $\pi^0$  kinematics

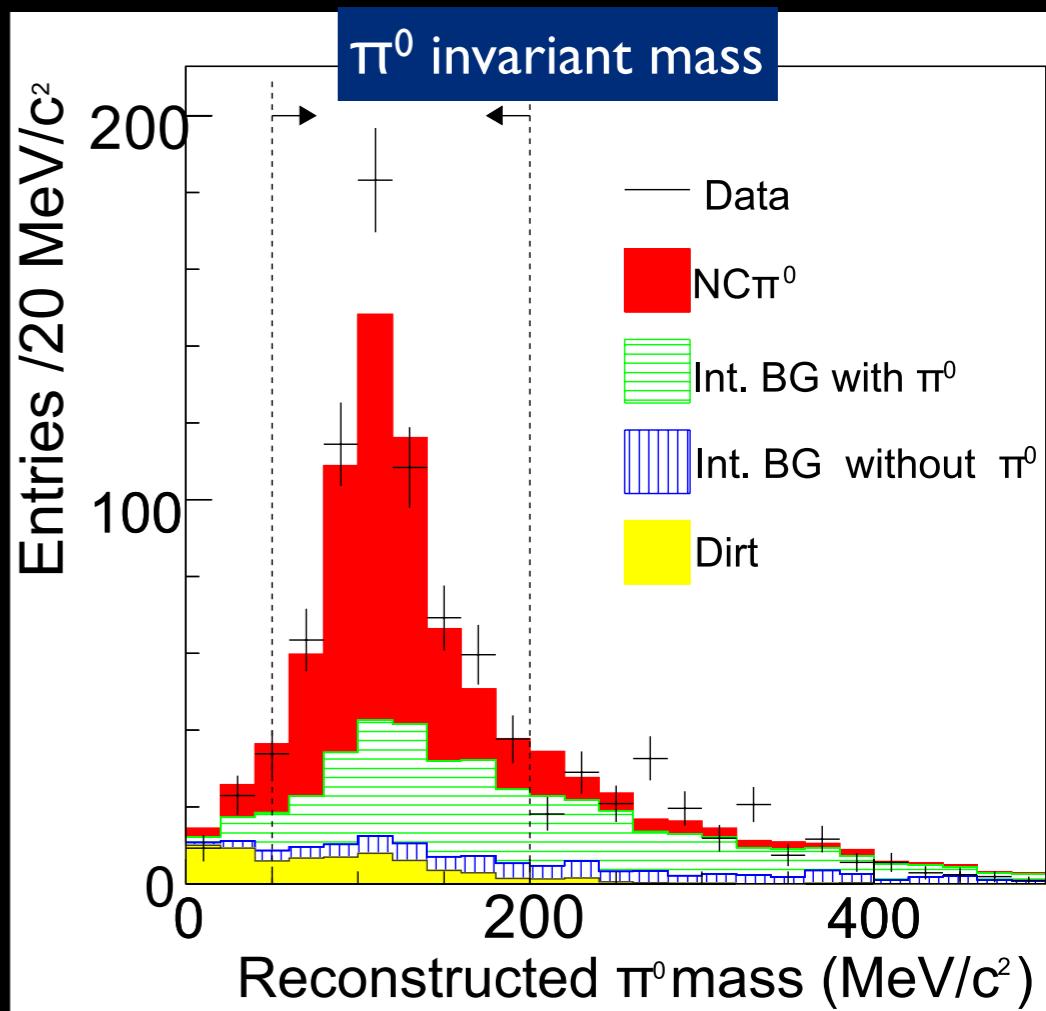
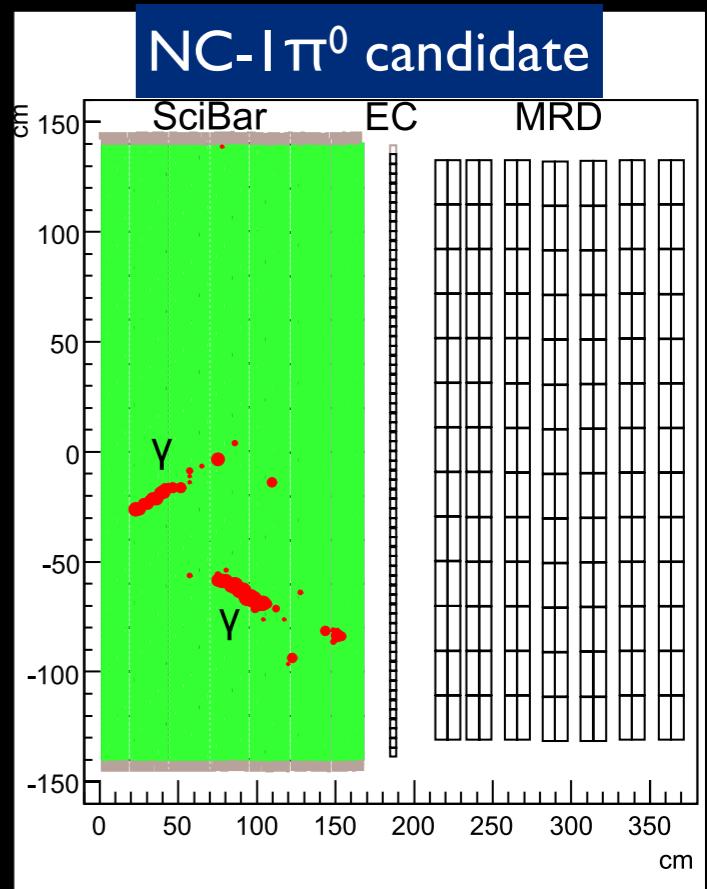


# NC- $\text{I}\pi^0$ @ SciBooNE

- Select events with 2  $\gamma$ -like tracks converting in SciBar and pointing to common vertex
- EC/MRD for energy leakage, CC background suppression
- $\pi^0$  vertex, mass and kinematics from  $\gamma$  candidates
- NC- $\text{I}\pi^0$  cross section relative to CC inclusive:

$$\sigma(\text{NC-}\text{I}\pi^0) / \sigma(\text{CC}) = (7.7 \pm 0.5 \text{ (stat)} \pm 0.5 \text{ (syst)}) \times 10^{-2}$$

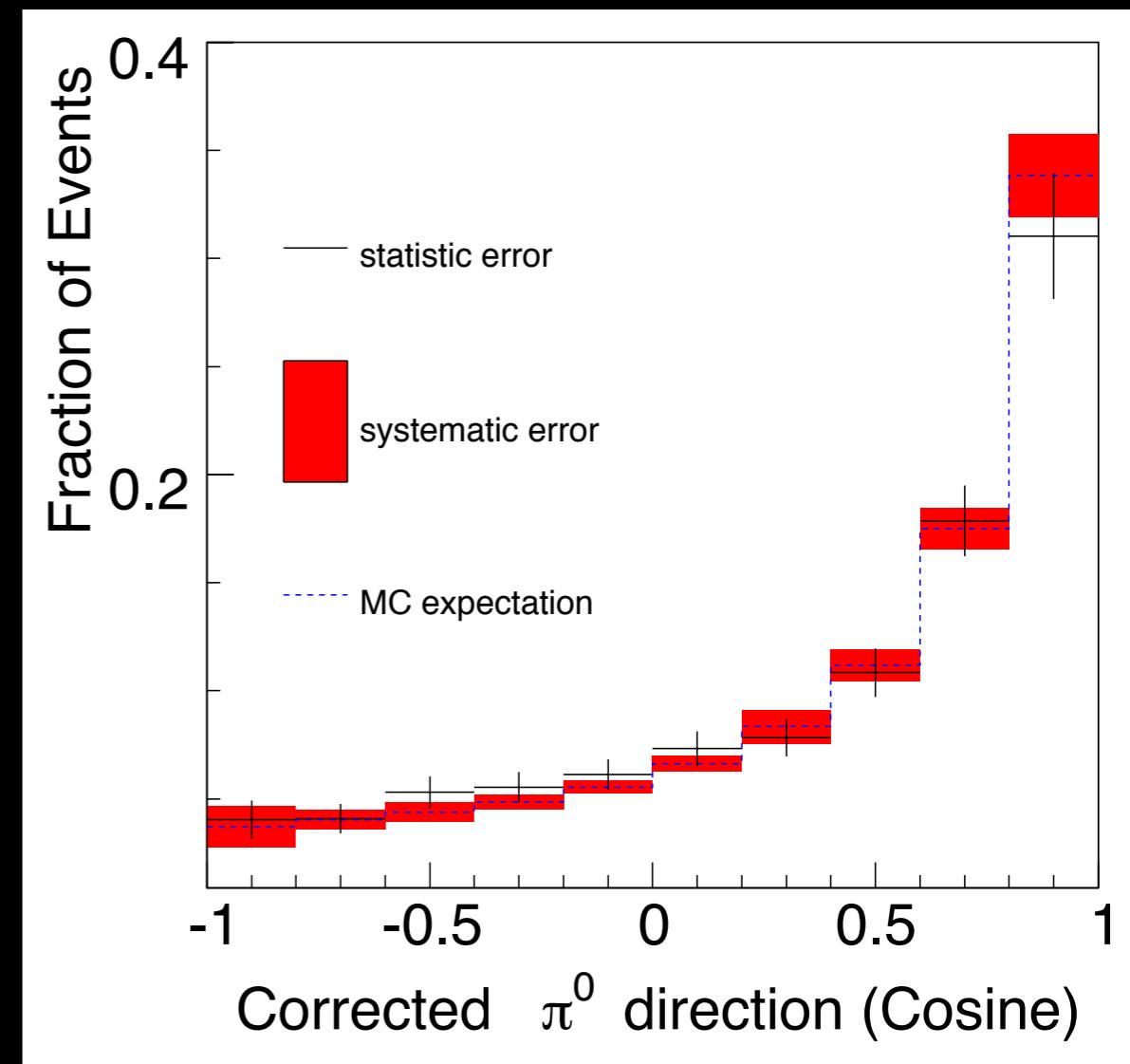
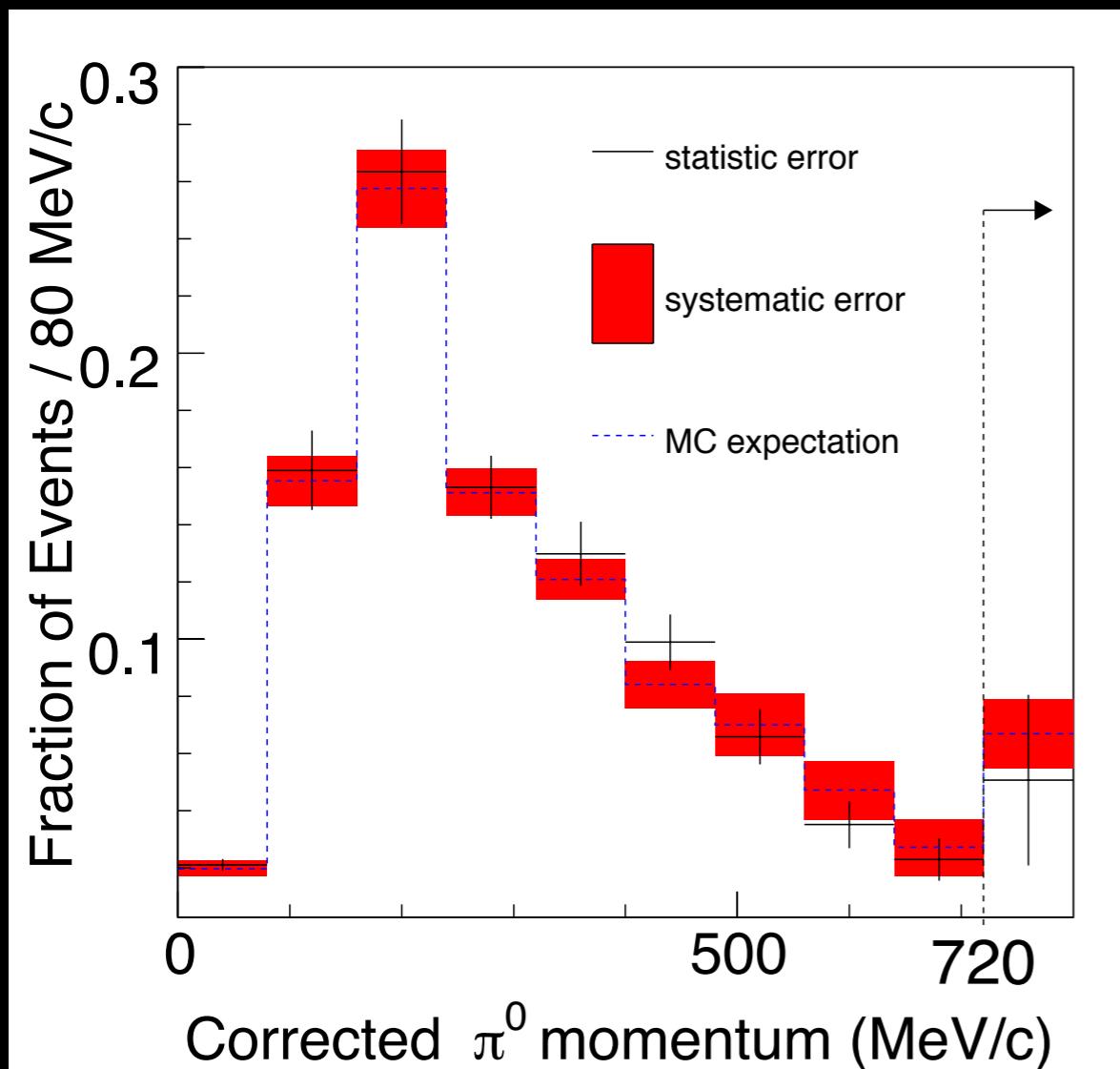
SciBooNE Coll., PRD 81:033004 (2010)



- 10% measurement, sufficient for T2K needs
- In agreement with expectation (NEUT):  $6.8 \times 10^{-2}$

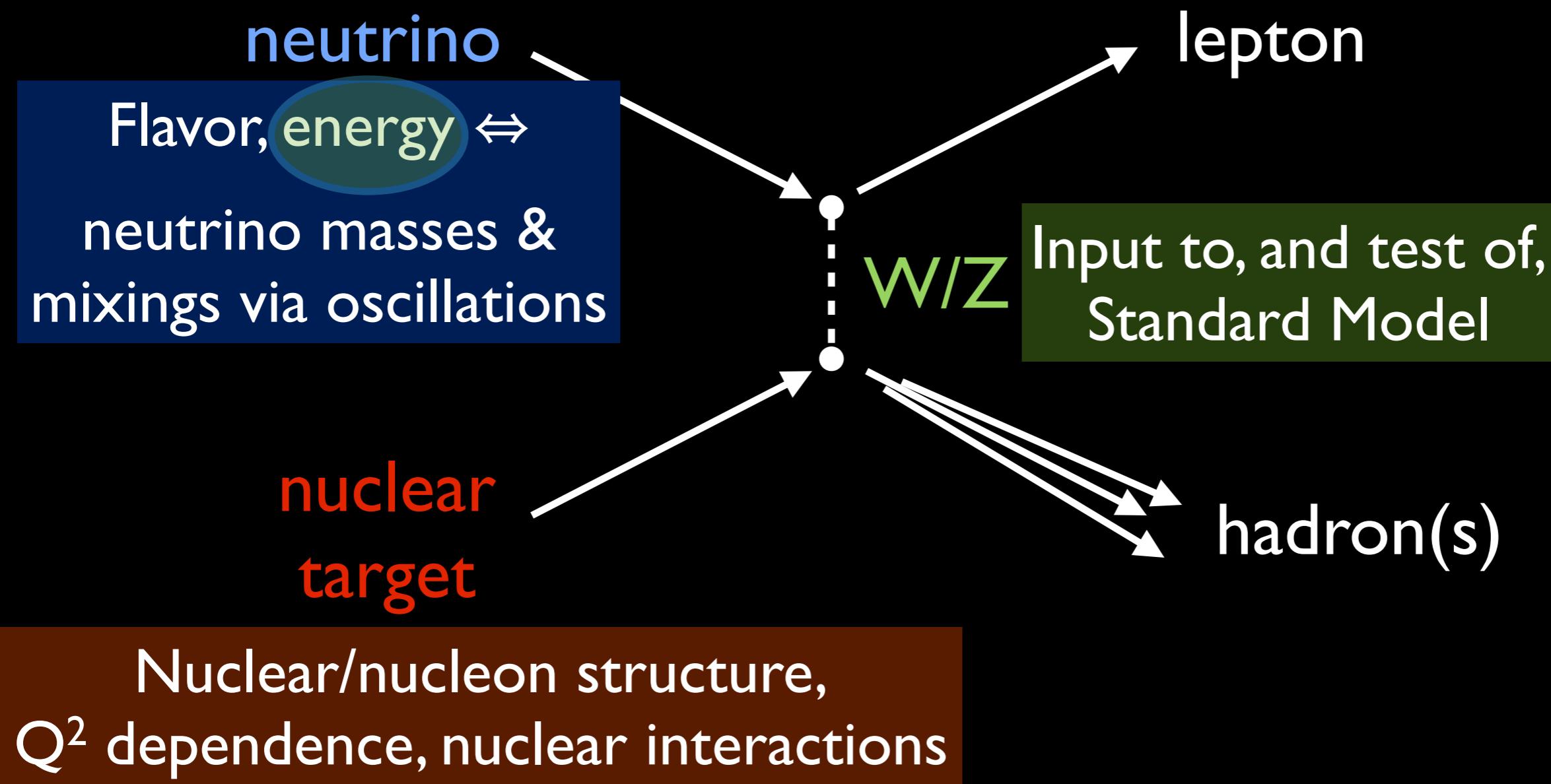
# NC- $\text{I} \pi^0$ @ SciBooNE

- $\pi^0$  production kinematics also in agreement with expectations



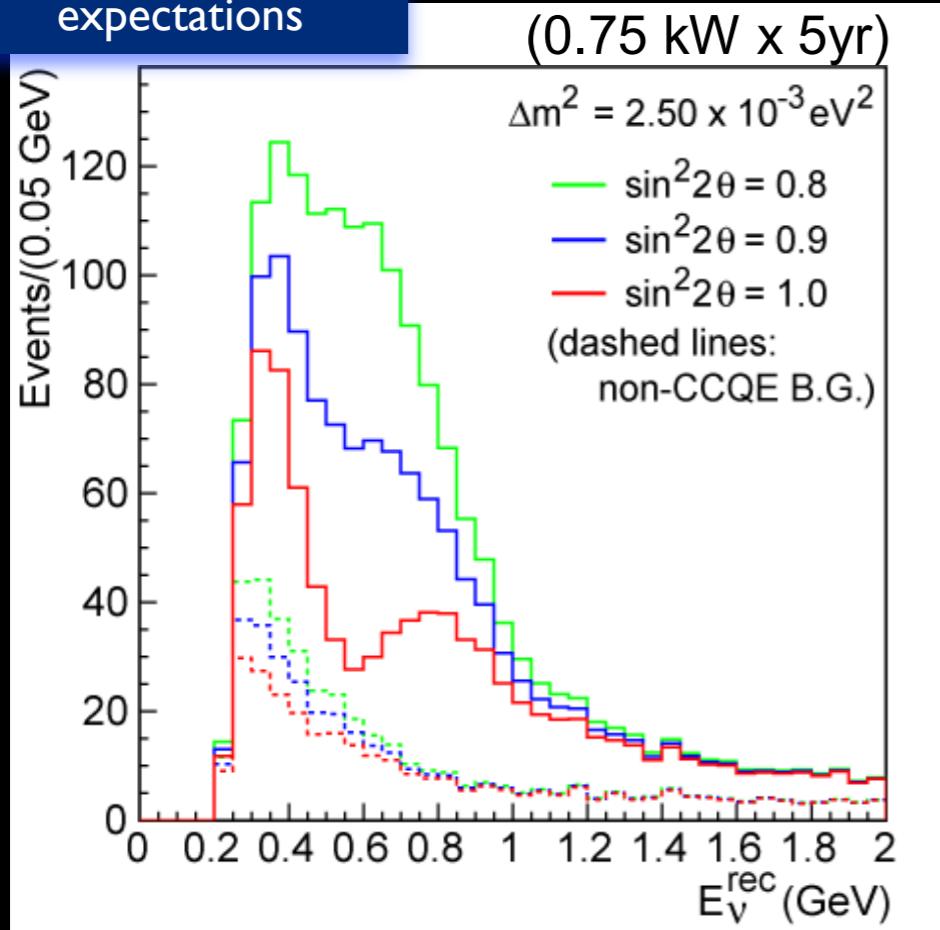
SciBooNE Coll., PRD 81:033004 (2010)

# Neutrino Interactions and Inferring Energy

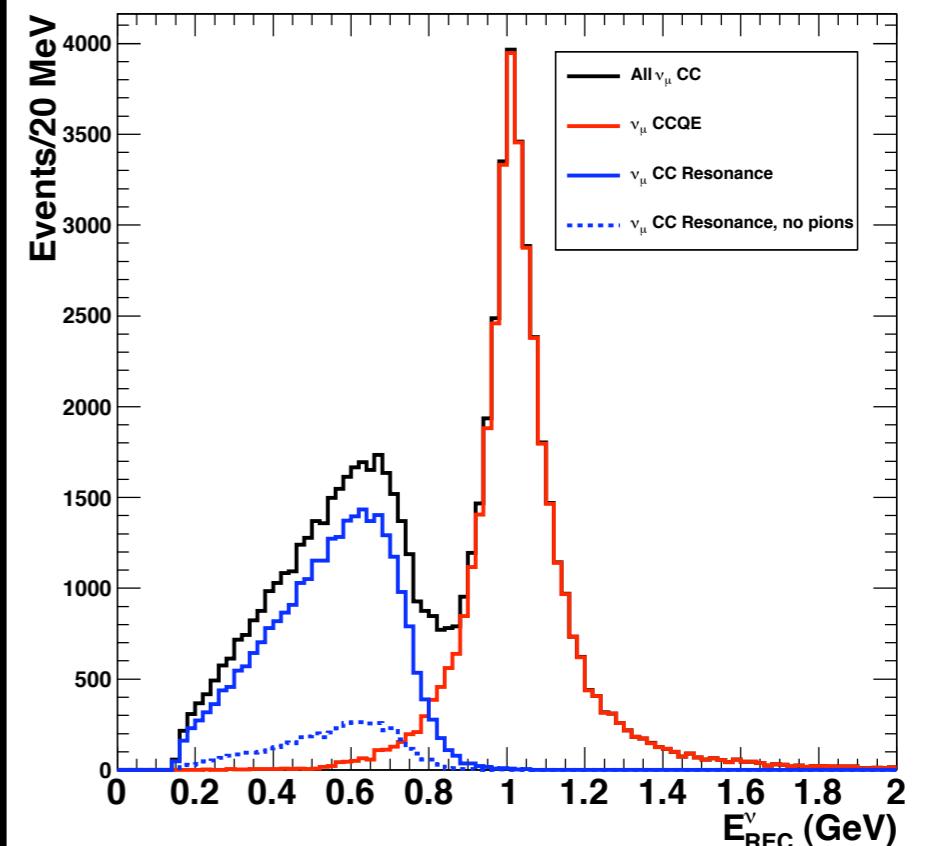


# Elastic or Inelastic?

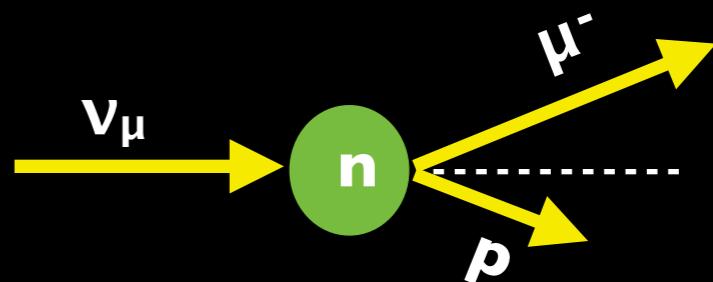
T2K  $\nu_\mu$  disappearance expectations



"kinematic" reconstruction of 1 GeV  $\nu_\mu$  CC in Genie



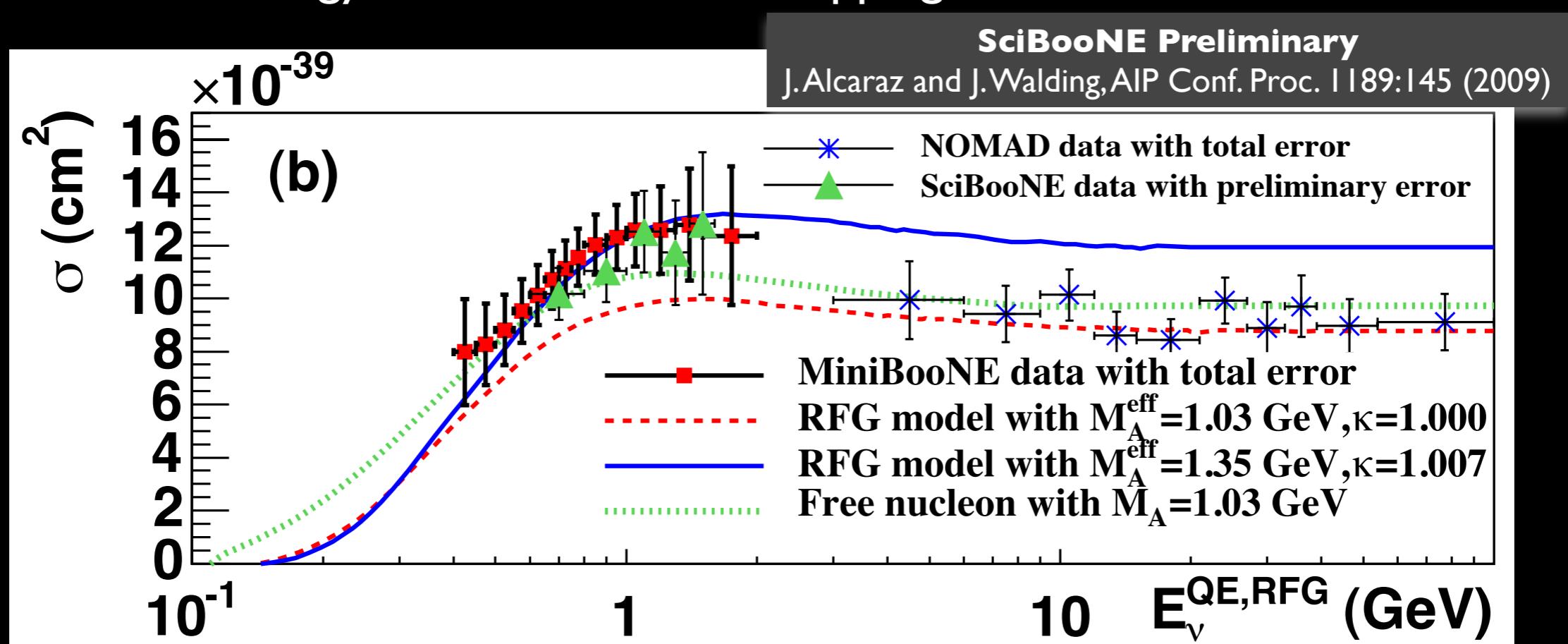
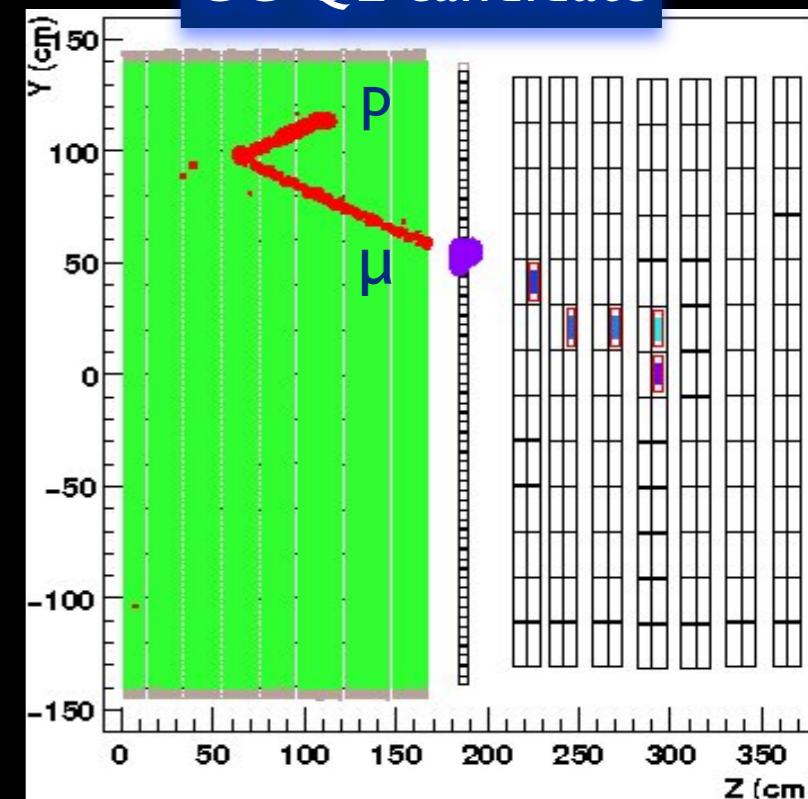
- To measure  $\nu_\mu$  disappearance due to oscillations:
  - $\nu_\mu$  flavor identification  $\rightarrow$  final state  $\mu^-$  powerful tag
  - neutrino energy  $\rightarrow$  measure  $\mu^-$  momentum, assume CC QE scattering and stationary target
- This kinematic determination of energy performs **differently** for elastic or inelastic interactions
- Important to measure not only overall CC inclusive cross section as a function of neutrino energy, but also **separate** elastic/inelastic contributions



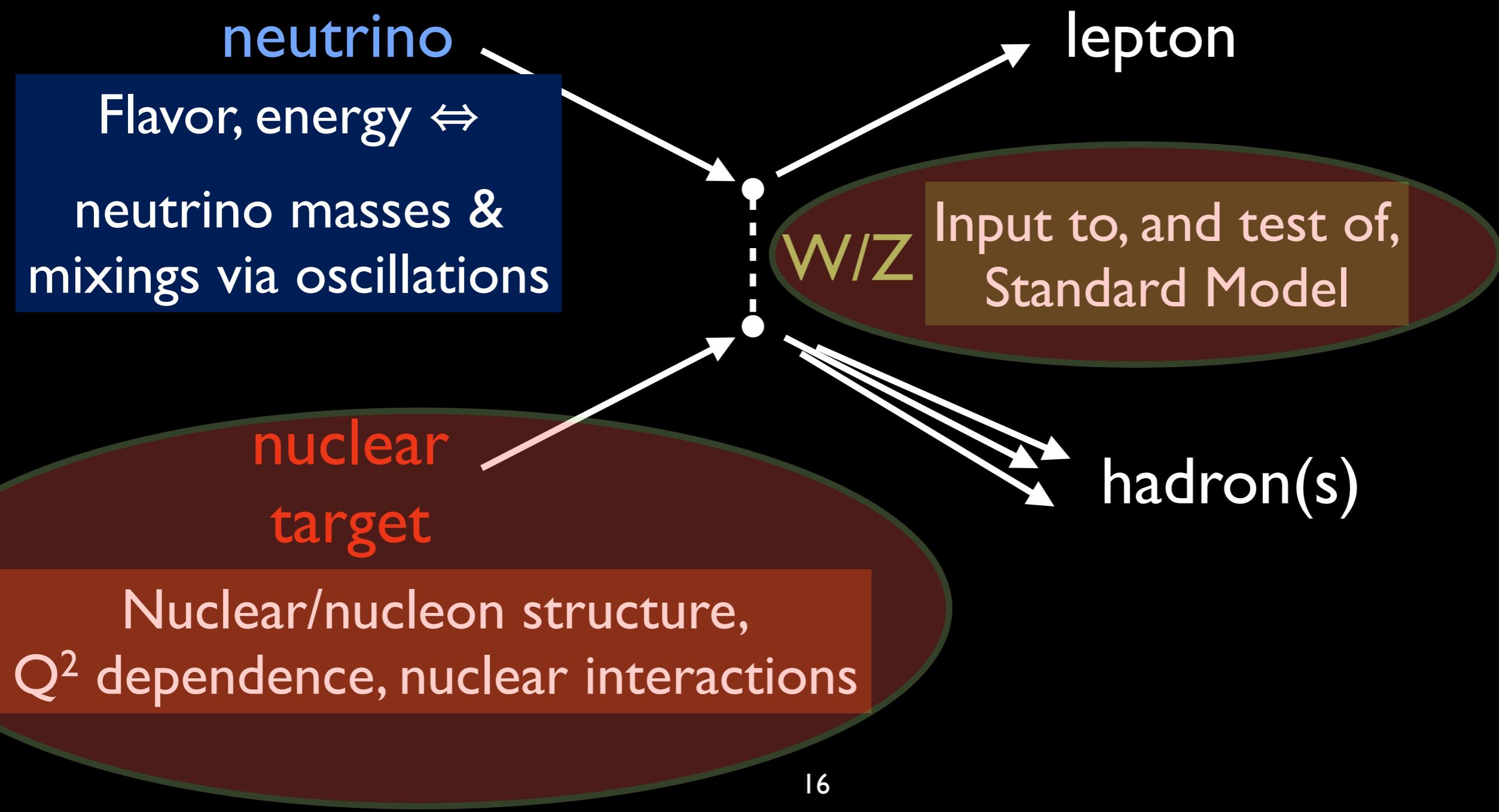
# CC QE @ SciBooNE

CC QE candidate

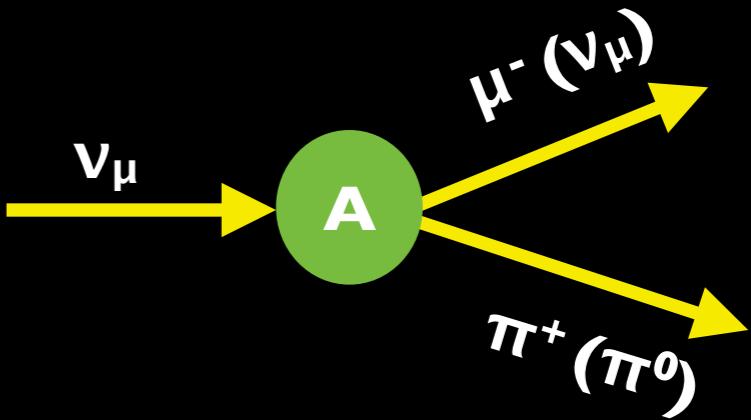
- Neutrino energy from kinematics of MRD-tagged muons
- Sensitivity to secondary tracks:
  - fit  $\mu$ ,  $\mu+p$ ,  $\mu+\pi$  samples to extract  $\sigma^{QE}(E_\nu)$  along with data-driven constraint on inelastic backgrounds
- Preliminary results not accurate enough to resolve apparent discrepancy between MiniBooNE and NOMAD
- Will extend low energy reach with SciBar-stopping muons



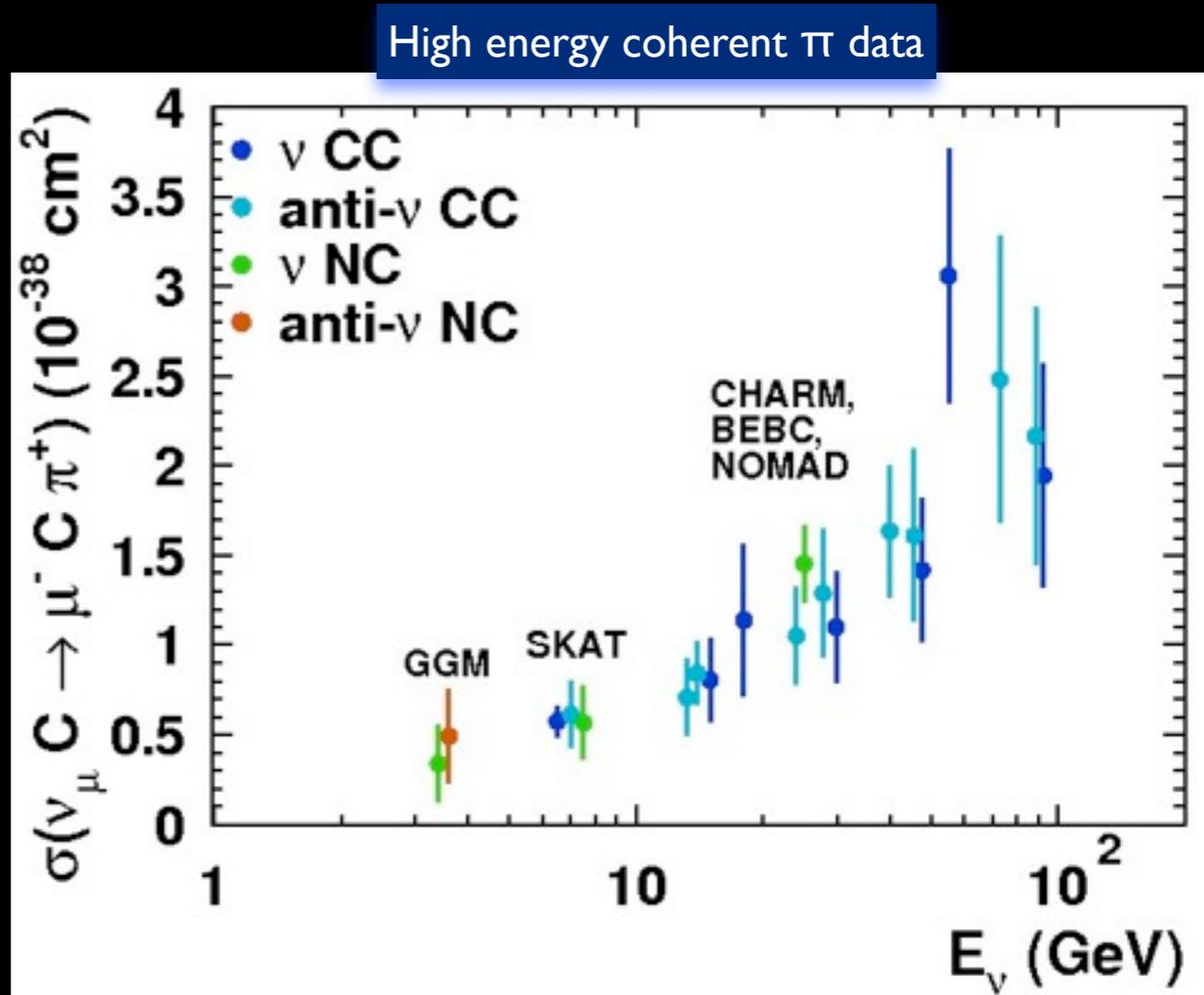
# Neutrino Interactions and Inferring Electroweak/ Nuclear Properties



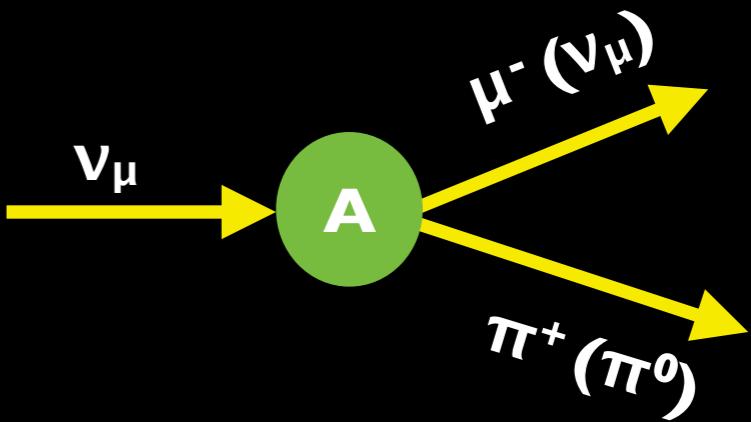
# Do We Understand Coherent $\pi$ Production?



- Coherent scattering off entire nucleus A:
- CC:  $\nu_\mu A \rightarrow \mu^- A \pi^+$
- NC:  $\nu_\mu A \rightarrow \nu_\mu A \pi^0$
- Small momentum transfer to hadrons:
  - No nuclear breakup, little nuclear recoil
  - Forward pion and lepton
- High energy ( $>3$  GeV):
  - Evidence in a number of experiments
    - Both CC and NC
    - Both neutrinos and antineutrinos
- Data well described by Rein-Sehgal model
  - $\sigma(\text{CC}) \sim 2 \sigma(\text{NC})$
  - $\sigma(\text{neutrino}) \sim \sigma(\text{antineutrino})$



# Do We Understand Coherent $\pi$ Production?



- Coherent scattering off entire nucleus A:

- CC:  $\nu_\mu A \rightarrow \mu^- A \pi^+$
- NC:  $\nu_\mu A \rightarrow \nu_\mu A \pi^0$

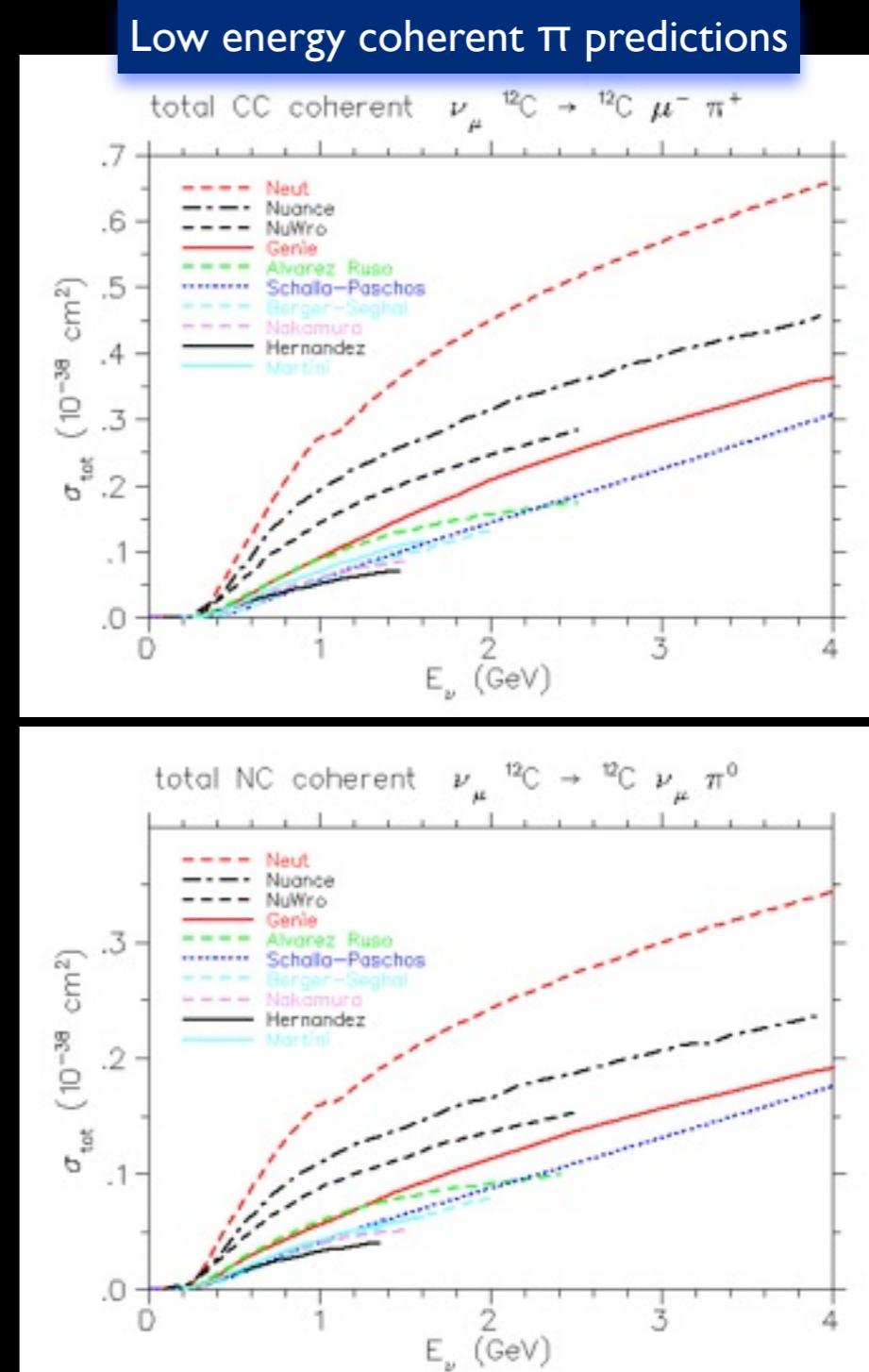
- Small momentum transfer to hadrons:

- No nuclear breakup, little nuclear recoil
- Forward pion and lepton

- Low energy (<3 GeV):

- Evidence in NC channel (Aachen-Padova, MiniBooNE)
- No evidence in CC channel (K2K), incompatible with Rein-Sehgal
- No clear prediction from theory

- SciBooNE: *first experiment to perform both CC and NC measurements at low energies*

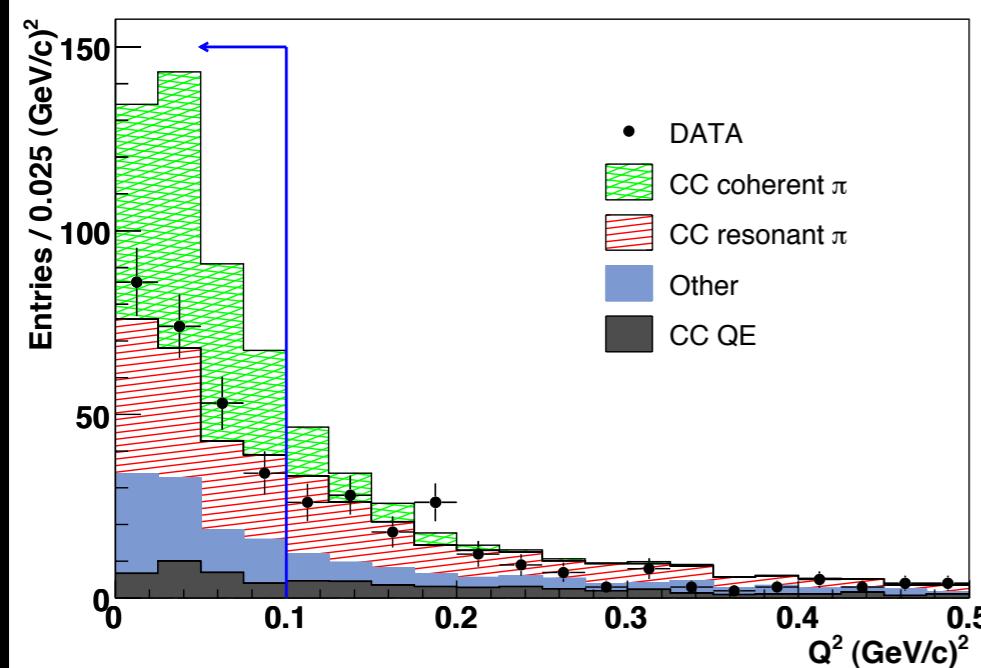


# Coherent $\pi^+$ Production @ SciBooNE

- Select  $\mu+\pi$  events with low vertex activity, forward pion, low  $Q^2$
- Additional CC samples to constrain backgrounds
- Two coherent  $\pi^+$  samples depending on muon range:

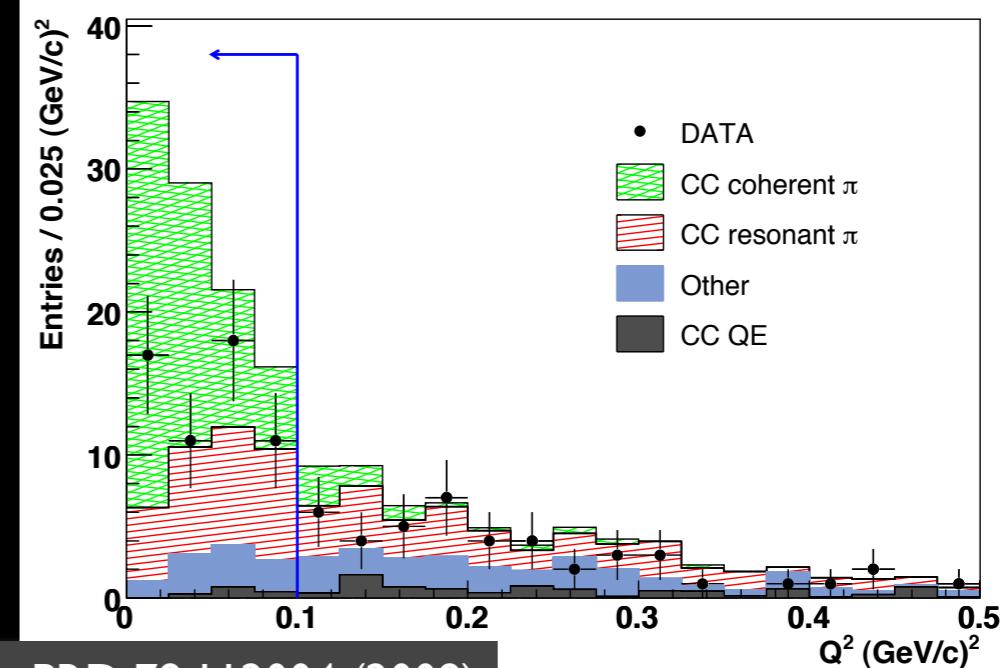
MRD-stopped muon:

- $\langle E \rangle = 1.1 \text{ GeV}$
- $\sigma(\text{CC coh})/\sigma(\text{CC}) < 0.67 \times 10^{-2}$



MRD-penetrated muon:

- $\langle E \rangle = 2.2 \text{ GeV}$
- $\sigma(\text{CC coh})/\sigma(\text{CC}) < 1.36 \times 10^{-2}$



SciBooNE Coll., PRD 78:112004 (2008)

- No evidence for CC coherent  $\pi$  production at SciBooNE
- Compatible with K2K data, incompatible with Rein-Sehgal model

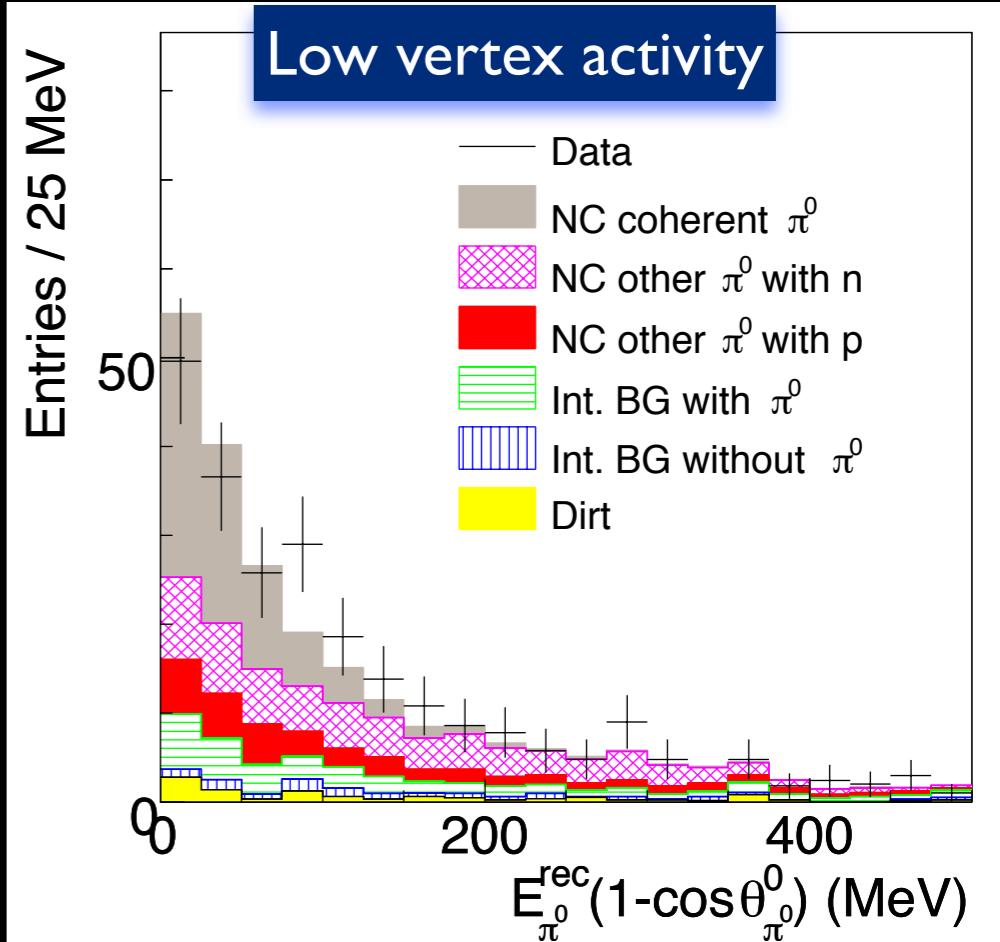
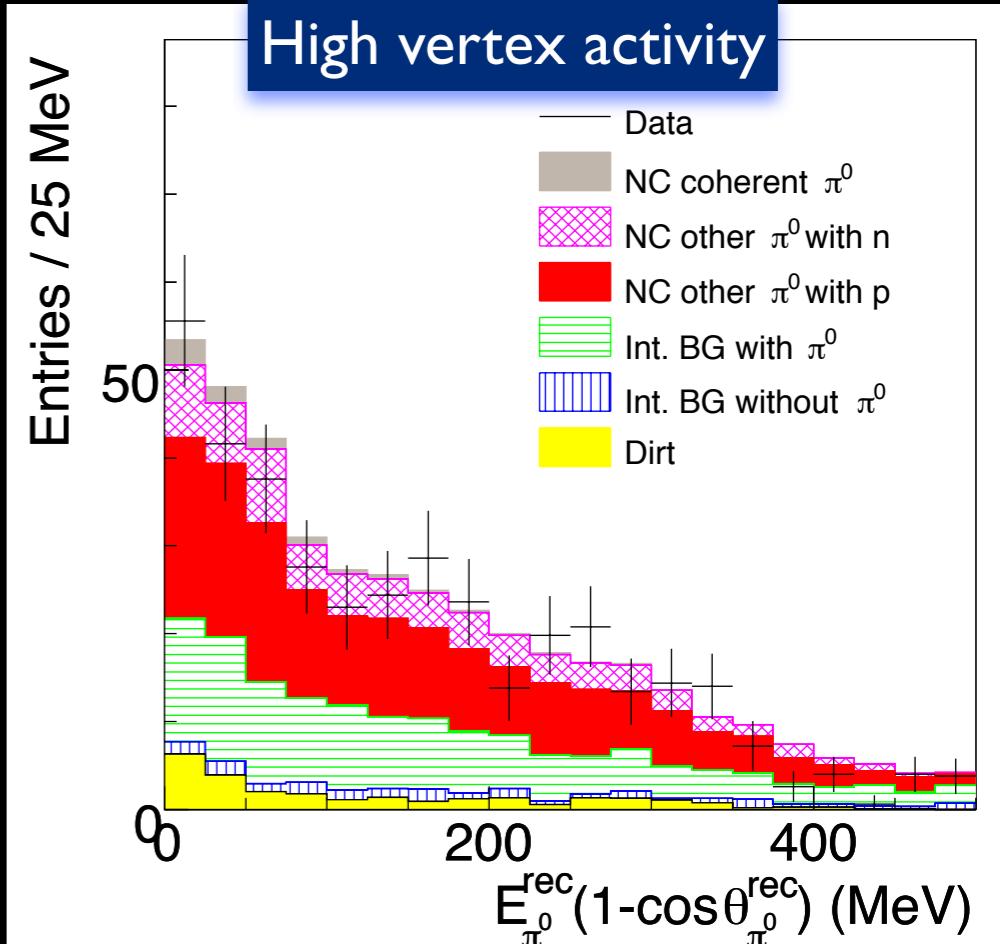
# Coherent $\pi^0$ Production @ SciBooNE

- Start from inclusive NC-1 $\pi^0$  event selection
- Separate into two sub-samples:
  - **low vertex activity:** signal sample
  - **high vertex activity:** background sample
- Fit the two  $E_{\pi^0}(1-\cos\theta_{\pi^0})$  distributions
- Coherent  $\pi^0$  production  $\Leftrightarrow$   
low momentum transfer  $t$  to nucleus  $\Leftrightarrow$   
low values for  $E_{\pi^0}(1-\cos\theta_{\pi^0})$

$$\sigma(\text{NC coh})/\sigma(\text{CC}) = (1.16 \pm 0.24) \times 10^{-2}$$

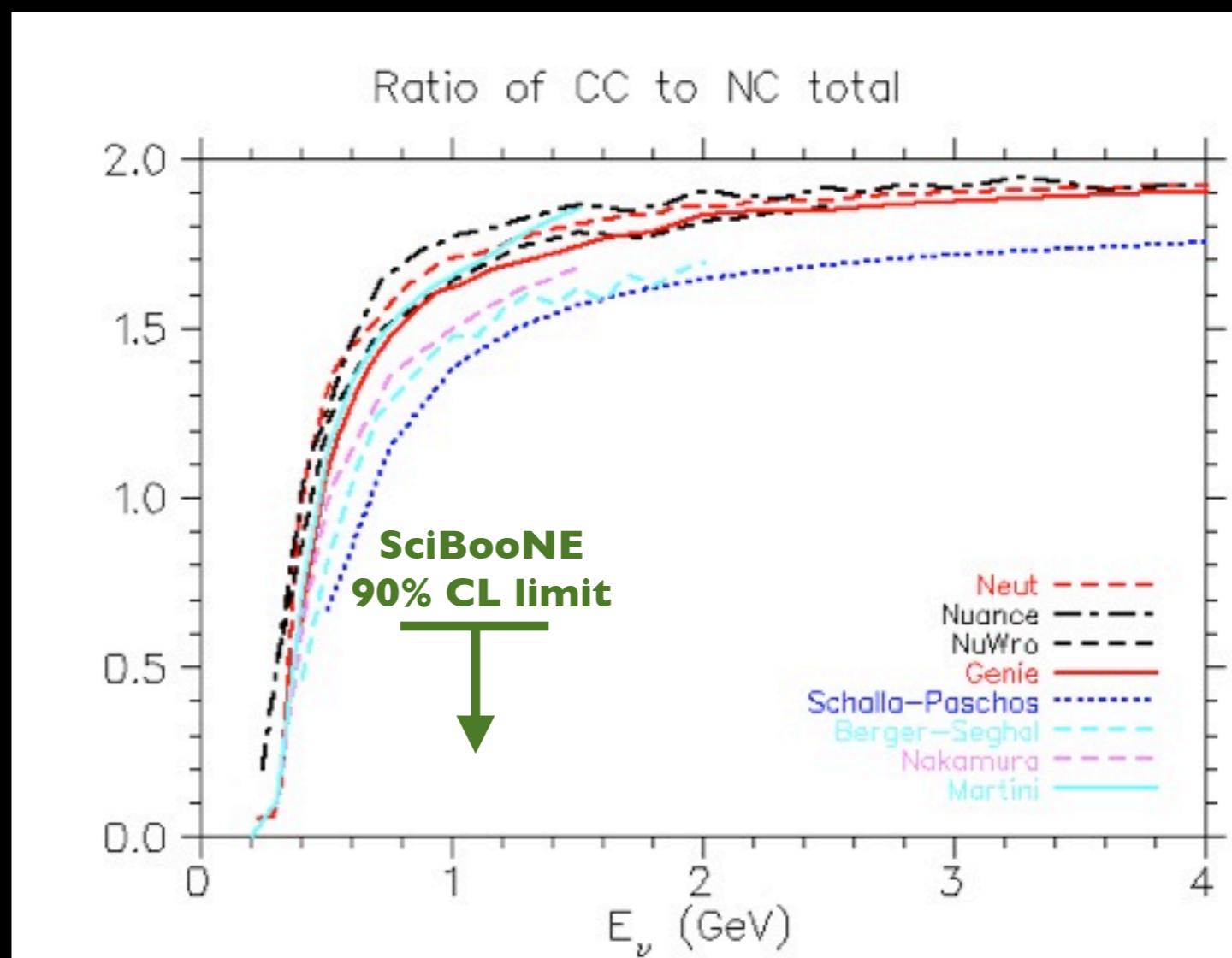
SciBooNE Coll., PRD 81:111102 (2010)

- In agreement with:
  - Rein-Sehgal prediction ( $1.21 \times 10^{-2}$ )
  - MiniBooNE data



# Coherent $\pi$ Production After SciBooNE: Data Confirmation, Theory Puzzle

- SciBooNE confirms:
  - No evidence in CC channel above level excluded by K2K
  - Evidence in NC channel at level seen by MiniBooNE
- No model capable of explaining CC/NC ratio upper limit measured by SciBooNE
- A puzzle to be resolved...



S. Boyd et al., AIP Conf. Proc. 1189:60 (2009)

SciBooNE Coll., PRD 81:111102 (2010)

# In Summary...

- Over past few years, renewed interest in low-energy neutrino interactions:
  - Sensitive oscillation searches require precision ν interactions measurements
  - Important for studying electroweak and nuclear physics as well
- With new intense sources, dedicated short-timescale experiments using fine-grained detectors can have major impact in the field: SciBooNE
- Only a taste of SciBooNE results given here. Many other analyses in the “pipeline”

- We have a roadmap for neutrino interaction measurements beyond SciBooNE



MINERvA

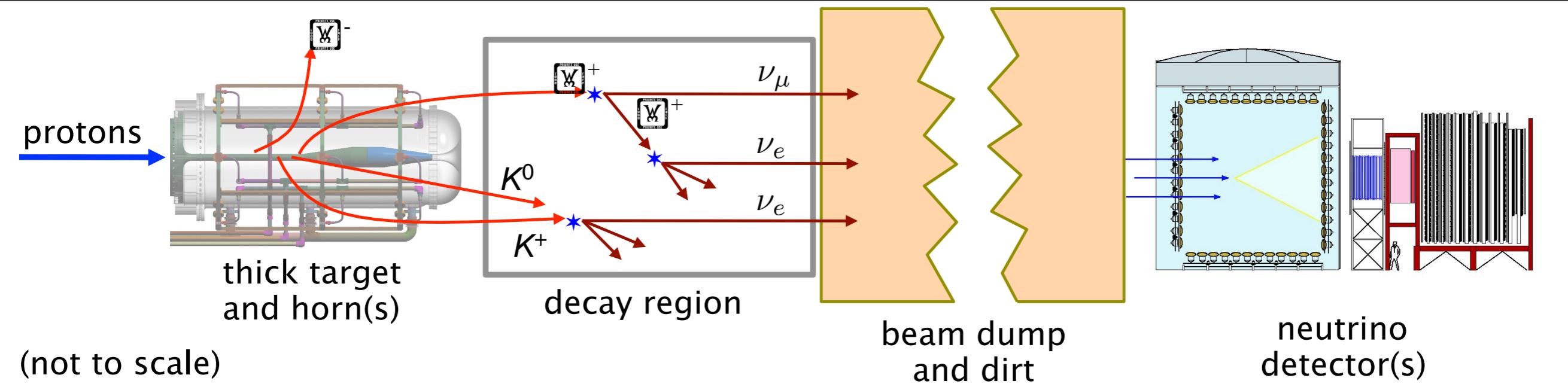


T2K ND280

# Backups

# Accelerator-Based Neutrino Beams

*Example of a conventional accelerator-based neutrino beam*



## Challenges:

- Neutrino rate measurements: degeneracy between  $\nu$  flux and  $\nu$  cross-sections
- Oscillation experiments alleviate impact of  $\nu$ -nucleus interaction uncertainties with:
  - two-detector setups (near and far from neutrino production)
  - detectors tagging neutrino flavors (typically muon and electron neutrinos)
- Still, neutrino-nucleus interaction uncertainties affect our understanding of how well:
  - we measure the neutrino energy
  - we measure/constrain backgrounds to oscillating neutrinos

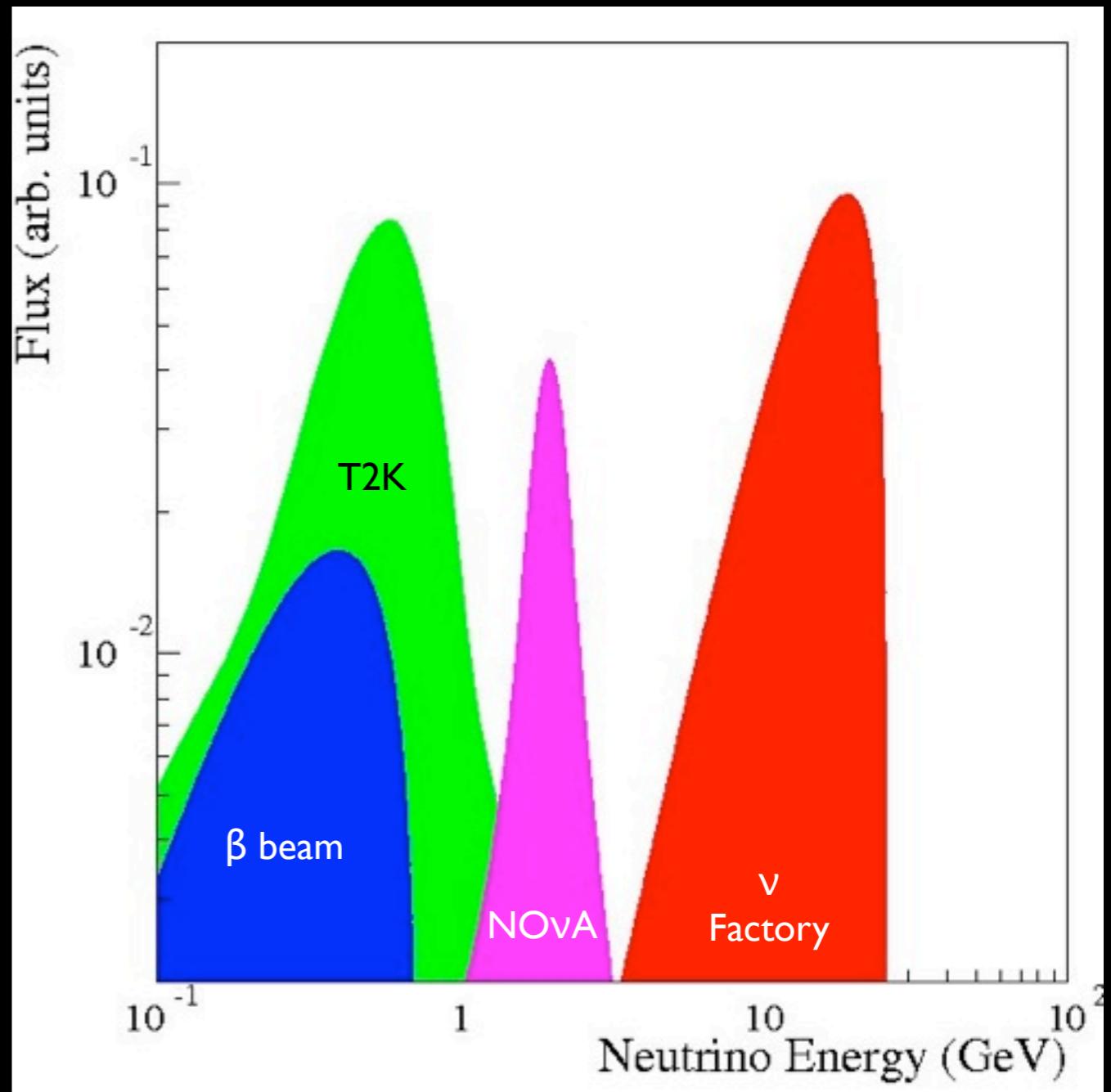
# Oscillation Physics: Which Neutrino Energies?

- Cross sections needed by future oscillation experiments across wide energy range

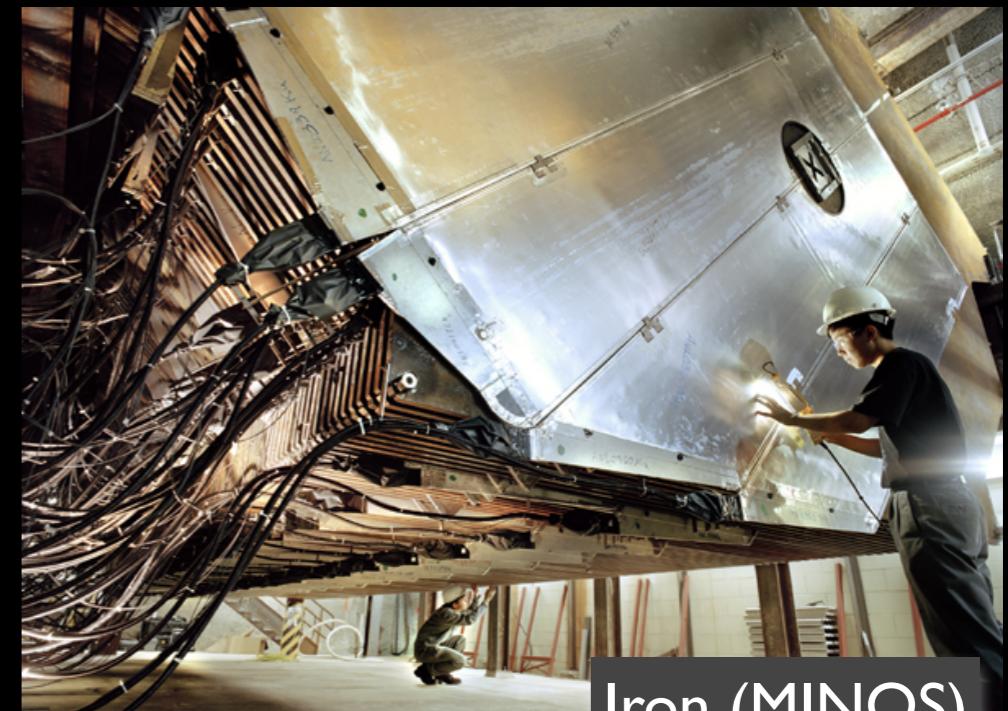
$0.3 < E_\nu < 50 \text{ GeV}$

- Current generation: low energies

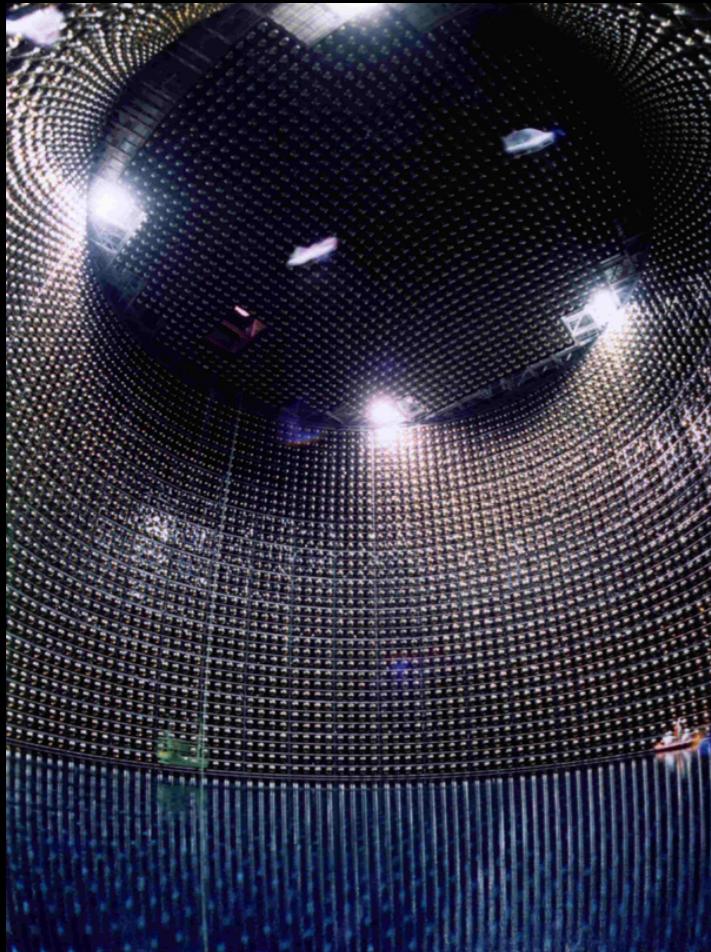
$0.5 < E_\nu < 5 \text{ GeV}$



# Oscillation Physics: Which Targets?



Iron (MINOS)



Oxygen (Super-K)



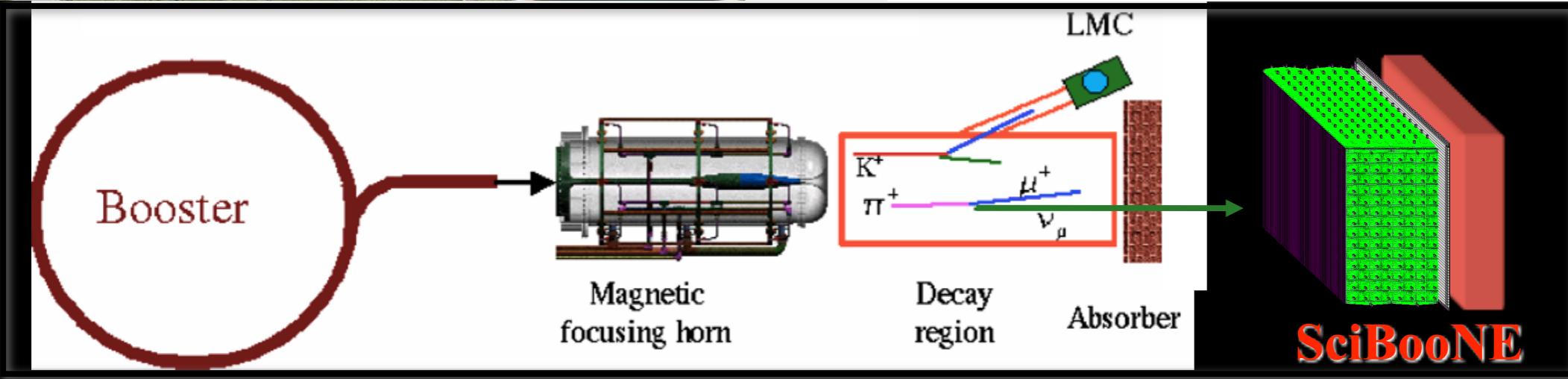
Argon (ICARUS)



Carbon (NOvA)

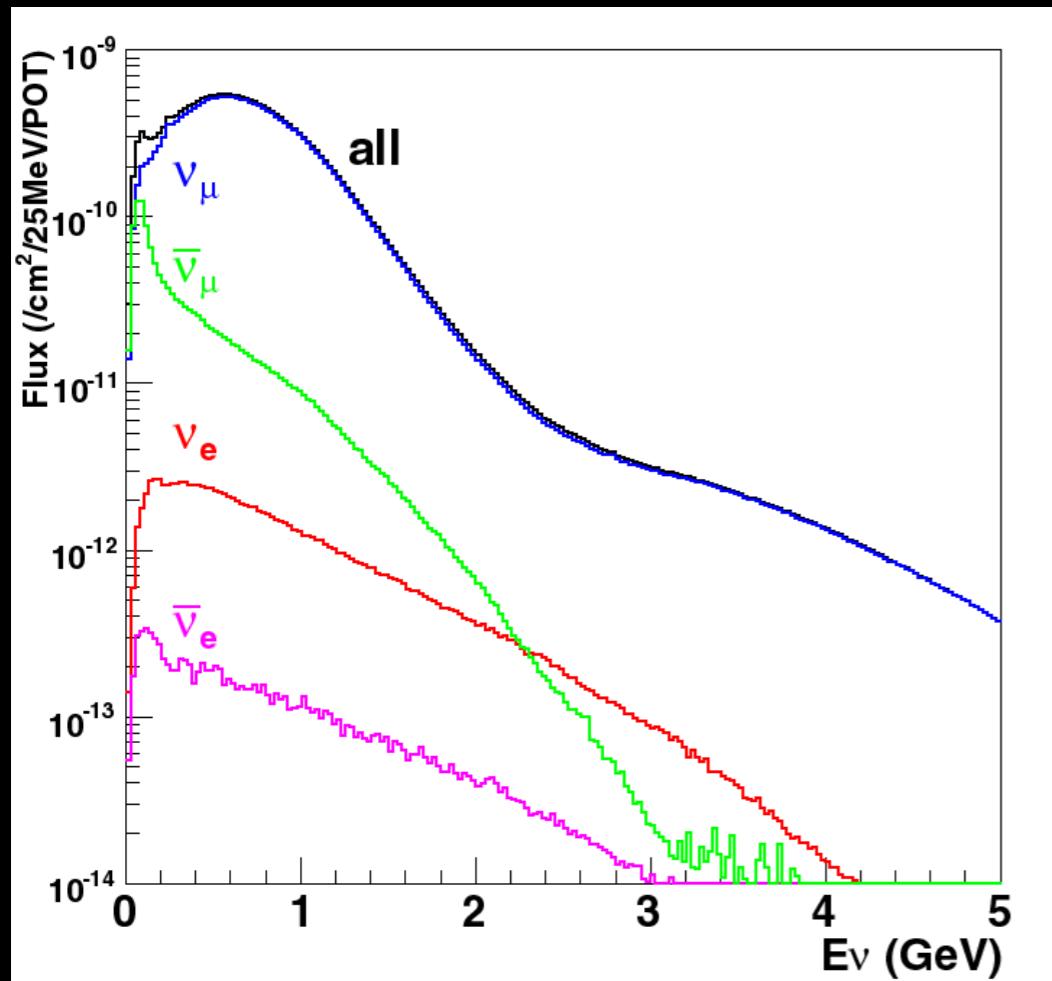


- Booster Proton accelerator
  - 8 GeV protons sent to target
  
- Target Hall
  - Beryllium target:  
71cm long 1cm diameter
  - Resultant mesons focused with magnetic horn
  - Reversible horn polarity
  
- 50m decay volume
  - Mesons decay to  $\mu$  &  $\nu_\mu$
  - Short decay pipe minimizes  $\mu \rightarrow \nu_e$  decay
  
- SciBooNE located 100m from the beryllium target



# Booster Neutrino Beam (BNB)

*Expected neutrino flux at SciBooNE  
(neutrino mode)*



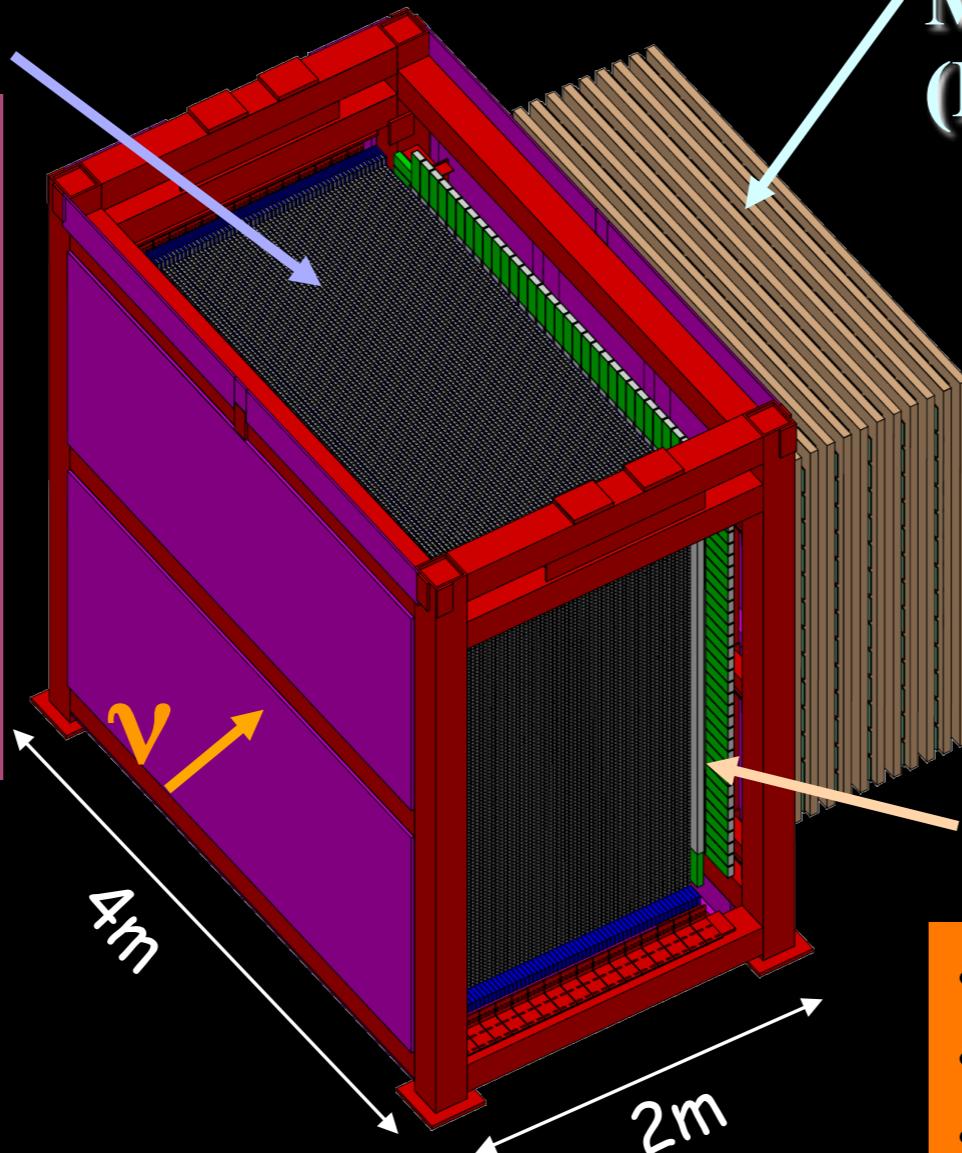
- Very intense
- Well understood, eg <10% flux normalization uncertainty (HARP)
- Neutrino mode:
  - *~0.7 GeV mean neutrino energy*
  - *93% ν<sub>μ</sub>, 6.4% anti-ν<sub>μ</sub>, 0.6% ν<sub>e</sub>*
- Antineutrino mode obtained by switching horn polarity

# SciBooNE detectors

## SciBar

- scintillator tracking detector
- 14,336 scintillator bars (15 tons)
- Neutrino target
- detect all charged particles
- p/π separation using dE/dx

Used in K2K experiment



DOE-wide Pollution Prevention  
Star (P2 Star) Award

## Muon Range Detector (MRD)

- 12 2"-thick steel + scintillator planes
- measure muon momentum with range up to 1.2 GeV/c

*Parts recycled from  
Past experiment*

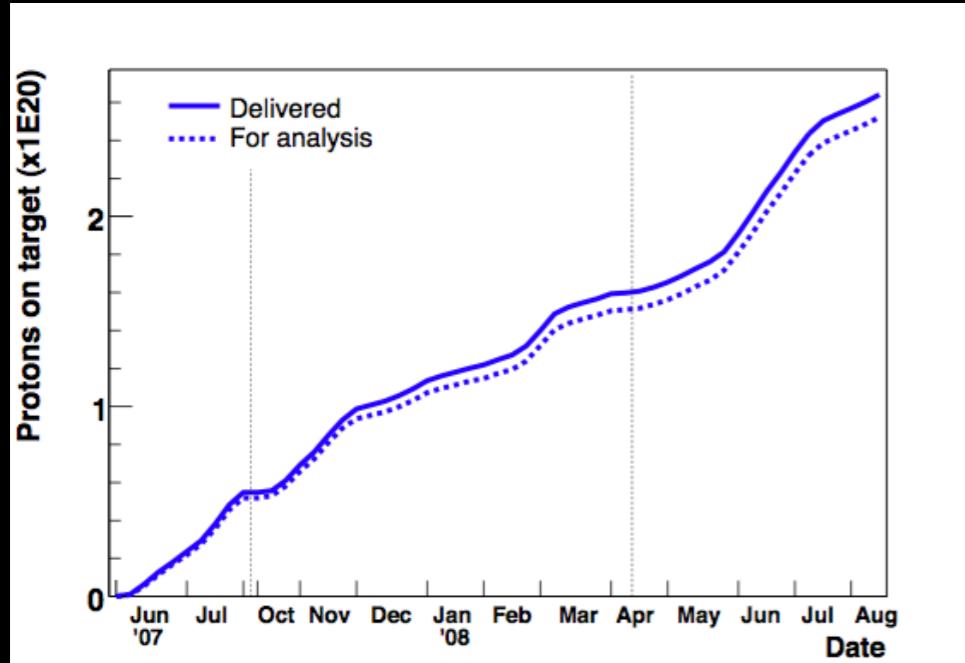
## Electron Catcher (EC)

- spaghetti calorimeter
- 2 planes ( $11 X_0$ )
- 32 modules per plane
- identify  $\pi^0$  and  $\nu_e$

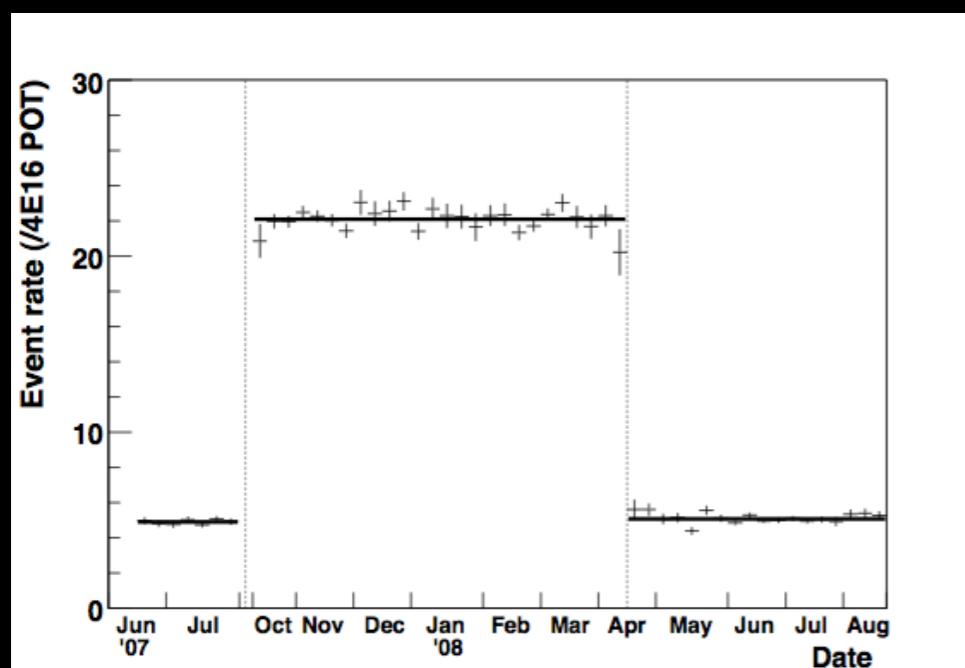
Used in CHORUS, HARP and K2K

# SciBooNE Data

*Number of Protons on target (POT)*



*CC event rate in SciBar*



Jun '07

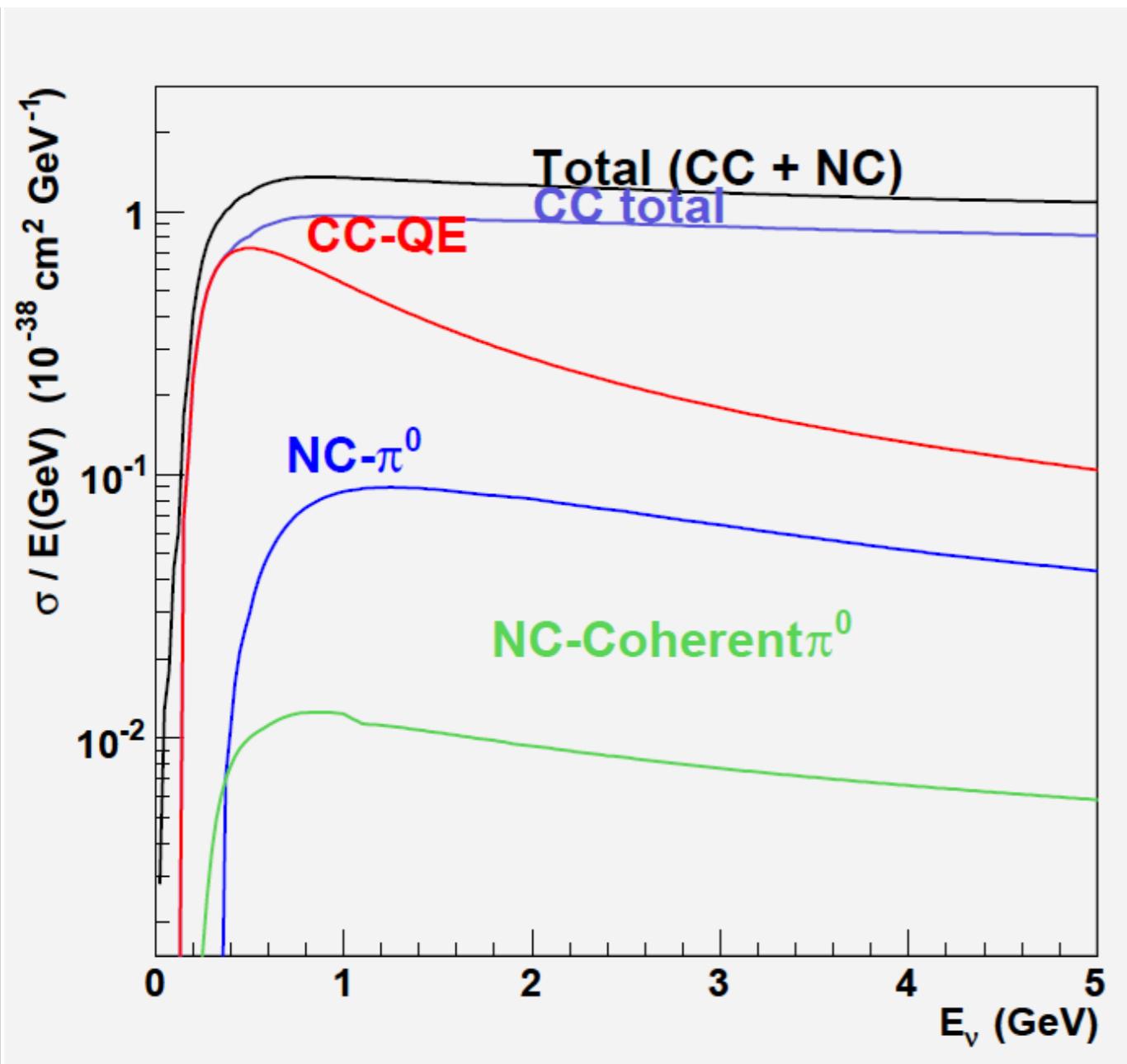
Aug '08

- Jun 2007 - Aug 2008
- 95% data efficiency
- $2.52 \times 10^{20}$  POT in total (x10 K2K-SciBar)
  - neutrino:  $0.99 \times 10^{20}$  POT
  - antineutrino:  $1.53 \times 10^{20}$  POT
- Results from neutrino data set presented

# NEUT

## Neutrino Event Generator

Used for Super-K, K2K,  
SciBooNE, T2K



Quasi Elastic (QE)  $\nu_\mu n \rightarrow \mu p$

Llewellyn-Smith formalism  
resonant  $\pi$  production

Rein-Sehgal (2007)

Coherent  $\pi$  production

Rein-Sehgal (2006)

DIS

GRV98 PDF

Bodek-Yang correction

For recoil nucleon in nucleus, the relativistic Fermi gas model of Smith and Moniz is used